CECW-EH-Y	**DEPARTMENT OF THE ARMY** **U.S. Army Corps of Engineers** **Washington, DC 20314-1000**	EM 1110-2-4000 Change 1

Manual
No. 1110-2-4000

31 October 1995

Engineering and Design
SEDIMENTATION INVESTIGATIONS OF RIVERS AND RESERVOIRS

1. This Change 1 to EM-1110-2-4000, 15 Dec 89:

    a. Adds Chapters 7 through 10.

    b. Updates the Table of Contents to reflect the addition of Chapters 7 through 10.

    c. Corrects page A-2.

    d. Corrects page B-8.

    e. Corrects pages F-2 and F-3.

2. Substitute the attached pages as shown below:

Chapter	Remove page	Insert page
Table of Contents		ix through xii
7		7-1 through 7-9
8		8-1 through 8-16
9		9-1 through 9-16
10		10-1 through 10-21
Appendix A	A-1 and A-2	A-1 and A-2
Appendix B	B-7 and B-8	B-7 and B-8
Appendix F	F-1 through F-4	F-1 through F-4

3. File this change sheet in front of the publication for reference purposes.

FOR THE COMMANDER:

Robert H. Griffin

ROBERT H. GRIFFIN
Colonel, Corps of Engineers
Chief of Staff

CECW-EH-Y Engineer Manual 1110-2-4000	Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	EM 1110-2-4000 15 December 1989
	Engineering and Design SEDIMENTATION INVESTIGATIONS OF RIVERS AND RESERVOIRS	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-4000

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Engineer Manual
No. 1110-2-4000

15 December 1989

Engineering and Design
SEDIMENTATION INVESTIGATIONS OF RIVERS AND RESERVOIRS

1. Purpose. This manual provides current guidance and engineering procedures for river and reservoir sedimentation investigations.

2. Applicability. This manual applies to all HQUSACE/OCE elements and field operating activities (FOA) having responsibility for the design of civil works projects.

3. General. Subjects covered are pertinent for planning, design, construction, and operation of flood control projects and navigation projects, and for permitting gravel extraction. The goal of a good design in a mobile boundary system is to provide safe and reliable projects which can be maintained at the design level of effectiveness with a minimum total investment of funds and effort. All designs are expected to give proper consideration to social and environmental impacts.

FOR THE COMMANDER:

ALBERT J. GENETTI, JR.
Colonel, Corps of Engineers
Chief of Staff

This Manual supercedes EM 1110-2-4000, 15 November 1961

DEPARTMENT OF THE ARMY
Office of the Chief of Engineers
Washington, D. C. 20314

EM 1110-2-4000

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CHAPTER 1

INTRODUCTION

Section I. General

1-1. Purpose. This manual was designed to guide the engineer in planning, conducting and reporting the results of a sedimentation study. Help is provided in selecting appropriate methods and levels of detail for studies typically encountered in river and reservoir engineering. The format is: point out potential problems, suggest acceptable approaches for their analysis, and identify checkpoints and pitfalls. This manual does not present detailed procedures for solving sediment equations, but a Sedimentation Glossary is provided to aid in reading the references.

1-2. Scope. This manual identifies typical sediment problems encountered in the development of flood control, navigation and hydropower projects in inland waters and presents appropriate procedures to resolve these problems.

a. Chapter 1 - Introduction. This chapter provides a summary of the requirements for sedimentation studies in the reports and continuing authorities for Civil Works projects in the Corps of Engineers. It was written as guidance for management.

b. Chapter 2 - Formulation and Planning of Sediment Studies. This chapter explains how to develop a sediment study plan. It includes guidance for identifying the sediment problem, defining the appropriate level of study, estimating the required time and costs for the work, organizing the tasks, and managing the investigation.

c. Chapter 3 - Sediment Yield. This is the first technical chapter. It presents systematic methods for determining the amount of sediment entering a project area.

d. Chapter 4 - River Sedimentation. This is the second technical chapter. It presents guidance for forecasting the future base condition of a stream system and for predicting the impact of a proposed project on that future base condition.

e. Chapter 5 - Reservoir Sedimentation. This is the final technical chapter. It presents guidance for conducting reservoir sedimentation studies.

f. Chapter 6 - Model Studies. Guidelines on the selection and application of models are discussed.

g. Appendices. The appendices contain examples that illustrate the concepts presented in the technical chapters.

1-3. Need for Sediment Investigation.

a. Physical Processes. Nature maintains a very delicate balance among the following variables: the water yield from the basin, the water velocity and depth; the concentration and size of sediment particles moving with the water; and the width, depth, slope, hydraulic roughness, planform, and lateral movement of the stream channel. That balance is dynamic not static.

b. Impact of Sedimentation on Projects. All surface water resource projects impose some changes on the above mentioned stream variables. In some instances, these changes increase the erosive forces to such an extent that the costs for providing necessary scour protection will exceed the potential benefits of the proposed project. In other instances, the rate of sediment deposition within various stream reaches may increase to the point where anticipated channel flood capacity or navigation depths are lost. The consequent costs of regularly removing the sediment depositions may be too great to maintain operation of the proposed project. These examples illustrate how sediment has impacted the design, operation and maintenance of project.

c. Impact of Project on Stream System Morphology. The second half of the question in water resource development is "to what extent will a project affect the behavior of the stream system?" When nature's balance is modified at one location, changes will migrate both up and down the basin. Sediment investigations need to estimate how far and how significant those changes might be.

1-4. Project Formulation. District offices in the Corps of Engineers follow established procedures in developing civil works projects. The typical functions and current project documents resulting from this procedure are listed on Table 1-1. An understanding of these documents and what they contain is needed to logically mesh the required sediment studies into the project planning and design process. Topics to include in sedimentation investigation reports are suggested in Section II of this chapter.

1-5. Level of Detail for Sediment Investigation. The Water Resources Development Act of 1986 (Public Law 99-662) as passed by the US Congress established new requirements of those local entities which sponsor the Corps water resource projects. Under these new requirements, local sponsors are liable for more of the project design and construction costs. Consequently, they are assuming a more active role in the design process. These new requirements have caused the Corps to adopt a policy that allows no project costs escalations once the local cost-sharing agreement (LCA) is signed. Because the LCA must be signed prior to initiation of project feasibility reports, firm project cost and time estimates must be established during the preparation of the first planning document - the reconnaissance report. This policy requires that the scope, time and cost requirements for sediment studies be established early in the project planning process.

TABLE 1-1. Studies, Reports and Continuing Authorities For Civil Works Projects

I. PLANNING FUNCTIONS
   A. Reconnaissance Reports
   B. Survey Reports
   C. Continuing Authorities
      1. Section 14 Emergency Bank Protection
      2. Section 103 Small Beach Erosion Projects
      3. Section 107 Small Navigation Projects
      4. Section 205 Small Flood Control Projects
      5. Section 208 Clearing and Snagging of Navigation Channels
      6. Section 221 Project Sponsorship Contract Assurances
   D. Recreational Master Plans
   E. Metropolitan Urban Studies
   F. Framework Studies (Level A)
   G. Regional or River Basin Studies (Level B)
   H. Implementation Studies (Level C)
   I. EPA 208 Studies, Wastewater Management

II. ENGINEERING FUNCTIONS
   A. Hydrology Design Memos
   B. Project Site Reports
   C. General Design Memos
   D. Specific Design Memos
   E. Water Control Management
      1. Reservoir Regulation Manuals
      2. Water Quality Reports
      3. Reservoir Sedimentation Investigations
   F. Notes on Sedimentation Activities
   G. CE-USGS Cooperative Stream Gaging Program

III. CONSTRUCTION-OPERATION FUNCTIONS
   A. Design Modifications
   B. Facilities Maintenance (Including dredging)
   C. Facilities Rehabilitation/Relocation
   D. New Cost-Share Facilities (Code 710)
   E. Project O&M Manuals

IV. REAL ESTATE FUNCTIONS
   A. Real Estate Design Memos
   B. Modification to Project Boundary Lines

1-6. <u>Staged Sedimentation Studies.</u>

a. General. In early stages of project formulation there is usually little or no sediment data and considerable pressure to forecast the type and

magnitude of sedimentation problems for project screening purposes. These conflicting positions can usually be resolved by initiating "staged sediment studies." Three stages are proposed: Sediment Impact Assessment, Detailed Sedimentation Study and Feature Design Sedimentation Study. These three levels provide information for decision makers as project formulation moves from preliminary to final results.

b. Stage 1. Sediment Impact Assessment.

(1) Purpose. The purpose of the sediment impact assessment report is to convey to reviewing authorities (1) the amount of effort expended to date in investigating sedimentation problems; (2) the amount and type of field data available for the assessment; (3) the anticipated impact of sedimentation on project performance and maintenance, and (4) the anticipated impact of the project on stream system morphology. This assessment is expected in the initial planning document with amplification as necessary in subsequent reports. A negative report is as important as one identifying problems.

(2) Scope. This report should discuss, at a minimum, the reservoir or river sedimentation problems identified in Chapters 4 and 5, as well as any unique problems anticipated for a project or site. It should forecast the remaining tasks needed to complete the sediment investigation.

c. Stage 2. Detailed Sedimentation Study.

(1) Purpose. The purpose of the detailed sedimentation study is to (a) refine problems reported in the sediment impact assessment (b) recommend corrective measures, and (c) calculate the effectiveness of these measures. The detailed study is conducted if the sediment impact assessment predicted an adverse sedimentation problem or if an on-going project is experiencing sedimentation problems.

(2) Scope. The scope of Stage 2 is assumed to be the same as Stage 1, but the depth of study in Stage 2 should be controlled by the level of technical details required to solve the problems whereas it was controlled by project formulation economics in Stage 1. The end product of stage 2 is a plan showing design features that handle the general sedimentation problems.

d. Stage 3. Feature Design Sedimentation Study. The purpose of the Feature Design Sedimentation Study is to protect the structure against failure from local scour of deposition and to establish special operational procedures as necessary.

e. Risks and Consequences.

(1) Risks. There are risks in utilizing the "staged study" approach. For example, screening of potential problems is proposed using data in hand. The end product is an assessment about the magnitude of potential sedimentation problems. The screening assessment is then refined as field data becomes available. However, there are gaps between available theories and the temporal and spacial variations in sedimentation processes. The only way to bridge those gaps is to confirm the empirical, analytical procedures with

measurements from the field. Therefore, staged sedimentation studies should adopt a project impact concept in which a safety factor, perhaps from 1.5 to 2 times the best initial estimate of the problem, is used to develop an impact on project costs. If such an impact does not affect basic go/no-go decisions, the sedimentation study can be staged and refined as the project moves through planning and design stages. However, when sediment problems appear to dominate project design and economics, the staged concept should be avoided in favor of a more defendable sedimentation study based on field data.

(2) Consequences. To follow the staged concept requires that planners and designers be prepared to modify basic project features, schedules, and economics as sediment data becomes available because there is presently no reliable method for either transposing, or calculating theoretically, bank erosion, channel location, or the sediment yield from an ungaged watershed. Examples are

(a) size and type of levee, flood wall, or channel feature;

(b) the size and type of dam or stilling basin;

(c) the type of outlet works or intake structures;

(d) the location and amount of land acquisition and relocations; and

(e) the reservoir operating rules

Section II. Reporting Requirements

1-7. General. A Corps project will seldom deal solely with sediment problems. Consequently, the reporting requirements for sediment studies are typically a part of the overall hydrologic and hydraulic portion of the reporting document. All project reports listed in Table 1-1 are expected to include at least a summary statement of the sediment conditions encountered in the proposed project. If no significant problem was found, present that for higher review in sufficient detail to justify the conclusion. Following is guidance on the specific information to be presented in those project reports which normally cover sediment conditions in detail.

1-8. Feasibility Report. The feasibility report consists of two phases as described in Planning Guidance Notebook.

a. Reconnaissance Phase. The initial phase is basically one of problem identification and preliminary (usually very qualitative) analysis as to the Federal interest in continuing the study. As a minimum, described historical sedimentation problems and predict a future base condition as if no project were built. The project study, design and construction costs are established for the local cost-sharing agreement. Consequently, existing sediment problems should be identified, the magnitude of the problem evaluated, and the method of future analysis described. The level of detail for further sediment studies should be defined.

(1) Project Features Influence Sedimentation Problems. If extensive modifications are proposed to the channel cross section, alignment or bank-full discharge or if water diversions or reservoirs are proposed, the possibility of sediment problems requires a considerable detail in the sedimentation analysis. The technical requirements that should be included are presented in reference [57].

(2) Operation and Maintenance. The consideration of channel maintenance and periodic dredging in the design of the proposed project should be discussed. Cost for the sediment monitoring program should be estimated. Reference [54] describes procedures for establishing a stream gaging program with the U. S. Geological Survey. Appendix K in this manual describes reservoir ranges, and the same concepts should also be applied to sediment ranges for channel projects.

b. Feasibility Phase. This phase will feature the detailed evaluation of the existing problem and the development of the recommended solution. A sediment impact assessment should be reported. It may require as little effort as a field reconnaissance interpreted with engineering judgment or as much effort as a period-of-record sediment routing analysis. The objective is to determine whether or not a sediment problem exists and, if so, whether or not it can be eliminated within the funds available for the project.

1-9. <u>Design Memorandum.</u> Whereas pre-authorization sedimentation studies are needed to determine whether or not a problem exists; design memoranda report the detailed design to handle the problem. In addition, these studies should design the sediment monitoring facilities needed for project operation and maintenance.

a. Analytical Techniques. Analytical techniques, numerical models and/or physical models are available to develop such solutions. No one method or technique is appropriate for all types of problems or studies. The engineer must determine the problem, select the means of analysis, and report the results so well-informed decisions can be made.

b. Real Estate Requirements. Analyses for real estate requirements should be explicitly presented. Plans should include access requirements and facilities for sediment monitoring and removal as needed to maintain and operate the project.

c. Reporting Requirements. Study and reporting requirements are similar to those previously described for feasibility studies. However, when sediment represents significant problems requiring extensive studies, a separate technical report, or a sediment appendix, may be appropriate.

1-10. <u>Post-Construction Reports.</u> Monitoring and reporting requirements for sedimentation should be included in the operation and maintenance manuals currently developed for all projects. The location of sedimentation ranges upstream, downstream and within the project limits should be displayed. Time periods for periodic resurveys should be specified. Guidance for dredging intervals for flood control channels should be given. Care of vegetation should be described relative to erosion, deposition and hydraulic roughness.

Studies performed during the construction/operations stage may rely more on the analysis of prototype measurements and data collection, such as a reservoir sediment survey or the periodic resurvey of sediment ranges than on modeling.

1-11. Continuing Authority Studies. An entire series of continuing authority reports (PL99, Type 201, Section 14, etc.) involve sediment analysis. Most of these studies are applicable only to limited, site-specific modifications however, and a simple sediment-impact analysis will suffice. The Type 205 Small Flood Control Continuing Authority Report is a possible exception. Potential flood control solutions proposed by a 205 study can be of sufficient magnitude to necessitate detailed evaluation of sediment. Since construction can follow the completion of a favorable 205 study, the level of detail would be similar to that in a combined survey report-design memorandum. Current planning criteria, presented in the Planning Guidance Notebook, describes the three stage process for a 205 study:

a. Initial Reconnaissance. This phase features a very brief and inexpensive study to determine if there is a Federal interest in continuing the project. Sediment reporting would largely consist of a presentation of any problems and the means of further study. Since this report is used to develop the local cost-sharing agreement, a firm estimate of the total time and cost for conducting the sediment studies is needed.

b. Expanded Reconnaissance. If a Federal interest is present, an Expanded Reconnaissance Report (ERR) is prepared prior to obtaining fiscal support from a local sponsor. This report is similar to much of the feasibility phase of the survey report procedures. Most of the hydrologic-hydraulic-sediment effort in the overall study report will be performed in the ERR. As a minimum, a sediment impact study would be done for the most feasible solution to the problem under study. If sediment plays a major role in the selection or feasibility of the recommended plan, detailed studies using sediment routing computer models would be performed and reported in the ERR.

c. Detailed Project Report. If the proposed project passes all tests for feasibility in the ERR, a Detailed Project Report(DPR) is prepared. The DPR is similar to a design memorandum, and is the design document for the recommended plan. The sediment analysis performed in the ERR may be updated in the DPR if additional data has been collected.

1-12. Sedimentation Reports. The Corps of Engineers has a responsibility for reporting data gathered, studies performed, and research activities undertaken in the sedimentation field. Annually, by 15 February, all Corps Field Operating Agencies and laboratories report the work performed in sedimentation over the past 12 months (ending 31 December). This information is combined with data from the other Federal agencies and published annually by the Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data in a publication entitled, "Notes on Sedimentation Activities." Reporting criteria is given in reference [56]. Details for the "Reservoir Sedimentation Investigation Program" are contained in Appendix K of this manual.

CHAPTER 2

FORMULATION AND PLANNING OF SEDIMENT STUDIES

Section I. Introduction

2-1. General. This chapter suggests guidelines and concepts to follow to insure the sediment study will identify the significant sediment problems and will produce a satisfactory analysis of alternatives for handling those problems.

2-2. Likelihood of Having Sediment Problems. There is no simple formula that predicts either the likelihood or the severity of sediment problems. However, in applying engineering judgement consider the following concepts:

a. Stable Channel Historically. When the existing channel is stable, the magnitude of the sediment problem for a project channel is generally proportional to the amount of deviation from the existing channel width, depth, slope alignment, vegetation environment, inflowing water discharge hydrographs, inflowing sediment concentrations, particle sizes in the inflowing sediment load, classification of sediment on the surface of the streambed, downstream stage-discharge rating curve, distribution of water between channel and overbanks, and irregularities allowed in the design geometry.

b. Unstable Channel Historically. When the existing channel is unstable, the magnitude of the sediment problem for the design channel will be sufficiently severe to require a detailed sediment study.

2-3. Categories of Sedimentation Problems. It is useful to group sediment problems into two categories:

a. impact of sediment on project performance for which the area of interest is the project reach; and

b. the impact of the project on the behavior of the stream system for which the area of interest extends to the limits of the project's influence on the morphology of the stream system.

2-4. Identification of Potential Problem Area. Sediment problems are not equally likely at all points along a project. In general, the potential is the greatest for the following project features.

a. Increased channel width

b. Bridge crossings

c. Abrupt breaks to steeper channel bottom slope

d. Reaches where the bottom becomes flatter

e. Cutoffs and changes in channel alignment

f. Any feature is braided reaches

g. The upstream approach to the project reach and the transition to the existing channel downstream from the project reach

h. Appurtenant structures in the channel, such as channel training structures

i. Tributaries entering the project

j. Water diversion points

k. Upstream from reservoirs and grade control structures

l. Downstream from dams

m. Lower reaches of tributaries

Section II. The Sediment Studies Work Plan

2-5. Purpose for the Sediment Studies Work Plan (SSWP). A "Sediment Studies Work Plan" is a document for the district's files which demonstrates that adequate attention has been given toward identifying potential sediment problems. If problems are identified, the SSWP then becomes the instrument for developing and organizing the sediment investigation so:

a. it can be completed in a timely and efficient manner;

b. the level of detail is appropriate to provide information necessary for decision makers at each level of project formulation;

c. the technical procedures and end products are acceptable to reviewing authorities.

2-6. Usage. The SSWP will be drafted and used at the District level. However, projects of unusual scope or complexity may require field meetings between District, Division and Office, Chief of Engineers(OCE) representatives to arrive at acceptable criteria and technical procedures. The SSWP is to be utilized:

a. by the working engineer as the sequence of tasks to follow in performing the investigation and the end products from each task.

b. by the project leader as a basis for contractual negotiations with outside entities such as the Waterways Experiment Station, the Hydrologic Engineering Center or private engineering firms; and

c. by managers as the basis for estimating cost, scheduling work and checking progress.

2-7. Contents of Sediment Studies Work Plan. The SSWP is a planning aid to establish the objectives listed below.

a. Problem Identification. The SSWP should establish in specific terms the nature and scope of the sedimentation investigation necessary for each level of project formulation.

b. Approach. The SSWP should provide a basis for selecting methods that are suitable for timely completion of the study. The selected methods should consider the degree of refinement appropriate for the particular study, the nature, extent and reliability of the available data. The level of detail expected in the end products should insure that major decisions about the overall project design and operation remain sound as more data and study results become available during the project planning and design process.

c. Time and Cost Estimate. The SSWP should establish a basis for providing a reliable time and cost estimate for completion of the study.

d. Schedule. The SSWP should establish the systematic sequence of activities necessary to meet the sedimentation requirements within the allowable time frame.

e. End Products. The SSWP should provide a basis for personnel involved in the project planning and design processes to reach a mutual understandings regarding end products from the proposed sedimentation investigation prior to making major expenditures for sediment studies. The end products should be stated in terms of how results from the sediment investigation will affect decisions to be made about overall project safety, efficiency, reliability, first cost, operational cost, maintenance cost, environmental factors, social factors and mitigation of adverse impacts resulting from the sediment problems.

f. Data Collection. The SSWP should provide a basis for advanced scheduling of data collection where such data is not currently available.

2-8. Level of Detail to be Included in the SSWP. The level of detail to be included in the Sediment Study Work Plan varies depending on the likehood of having sediment problems and by the size of the project. Cite evidence from other, similar, projects operating in the area as well as studies for other projects to justify the degree of detail selected.

2-9. Sequence of Tasks in Developing the SSWP.

a. Boundary of Study Area. Establish the size of the study area which, in turn, will determine the amount of work that needs to be addressed with the SSWP. (The potential for the impact of the project on the stream system extends beyond the project boundary.) See chapters 4 and 5 for a more complete discussion of size of study area.

b. Objective. Write an objective statement for the sedimentation investigation. Identify and quantify existing constraints - such as: funding, time available for the study, manpower availability and data

availability. Recommend a course of action that will remove constraints to the maximum extent possible.

c. Problem Identification. By studying quadrangle maps of the project area, pertinent project features, soil classification maps, and aerial photographs, and by field reconnaissance, potential problem areas can be identified and noted on the maps. Use the location, number and type of problems as an aid for selecting methods for analysis, for assessing the adequacy of available data, and for preparing time and cost estimates.

d. Data Inventory. Prepare an inventory of available data by type: geometric, hydrologic, hydraulic, sedimentary, and land use data. Use the boundary of the study area as a guide for selecting gages and displaying spatial distributions. Use historical stability and project life in selecting time periods. Use specific project features to justify data requirements.

e. Recommended Approaches. Chapter 1 gives general guidance and the technical chapters give more detailed guidance on "Staging Sedimentation Studies." Perform a Sediment Impact Assessment for the project to determine the probable severity of sediment problems. Based on that result itemize the necessary tasks for completing the staged sedimentation investigations.

f. Time and Cost Estimate. Estimate the time and cost for each task in the itemized list. Beware of the subtle activities which are required to manage large quantities of data. i.e. Sediment studies require spatial and time dependent data sets describing geometry, hydrology, hydraulics, sediment and land use parameters. For example, the cost for assemblying such data is always considered; however, there are additional costs for converting, manipulating and displaying data that are often omitted. Another example, the analysis of historical boundary conditions is obviously needed for each inflow and outflow point around the project boundary to confirm the model by reconstituting historical events, but project performance depends on extrapolating boundary conditions into the future. This is often a more complicated analysis than is required for the historical calculations and is often omitted from estimates. A final example regards the analyses of proposed project designs, an obvious need; however, the analyses of the existing stream conditions during recent floods or droughts as well as the predicting of a future "do-nothing case" are sometimes neglected when estimating time and cost. Any one of these examples can be a formidable task because of the large quantity of data involved. In addition to these, there may be other tasks that are specific to your investigation. Estimate the number of man-days, by grade, for each category and sum to provide the time and cost estimate for the sediment investigation.

g. Review. The above should be developed and reviewed at the District level. However, division and OCE representatives may also be included, depending on the scope and complexity of the proposed project.

2-10. Data Sources.

a. General. The data that will be needed to develop the SSWP should come from office files, from other federal agencies, from state or local agencies, and from the team making the field reconnaissance of the project site.

b. U. S. Geological Survey (USGS). USGS topographic maps and mean daily discharges are used routinely in hydraulics and hydrology studies and are common data sources for sediment studies, also. However, mean daily flows are often not adequate for sediment studies, and data for intervals less than one day or stage-hydrographs for specific events can be obtained, through strip-chart stage recordings, by special request. It may be preferable to use USGS discharge-duration tables rather developing such in house, and these are available through the state office for each long-record gage. Water quality data includes suspended sediment concentrations and grain size distributions. Published daily maximum and minimum sediment discharges for the year and for the period of record are available as are periodic measurements of particle size gradations for bed sediments.

c. National Weather Service (NWS). There are cases where mean daily runoff can be calculated directly from rainfall records and expressed as a flow-duration curve without detailed hydrologic routing. In those cases use the rainfall data published monthly by the National Weather Service for each state. Hourly and one-day interval rainfall data, depending on the station, are readily accessible. Shorter interval or period-of-record rainfall data would require contact with the NWS National Climatic Center at Asheville, North Carolina.

d. Soil Conservation Service (SCS). The local SCS office is a good point of contact for historic and future estimates of land use, land surface erosion, and sediment yield. They often have soil maps, ground cover maps and aerial photos from periodic overflights of watersheds which can be acquired and used to site specific estimates of sediment yield. Input data for the Universal Soil Loss Equation is often available for much of the United States. The SCS also updates reservoir deposition studies for hundreds of reservoirs throughout the country every 5 years, providing a valuable source of measured sediment data.

e. Agricultural Stabilization & Conservation Service (ASCS). This agency of the Department of Agriculture accumulates aerial photography of crop lands for allotment purposes. However, those photographs will include the streams crossing those lands and are extremely valuable for establishing historical channel behavior because overflights are made periodically.

f. Corps of Engineers. Since the Corps gathers discharge data for operating projects and for those being studied for possible construction, considerable data from the study area may already exist. The Corps has acquired considerable survey data, aerial and ground photography, and channel cross sections in connection with flood plain information studies. Corps laboratories have expertise and methods to assist in both the preparation of the SSWP and the implementation of it.

g. State Agencies. A number of states have ongoing climatologic, hydrologic, and sediment data collection programs. Topographic data drainage areas, stream lengths, slopes, ground covers, travel times, etc are often available.

h. Local Agencies, Businesses and Residents. Land use planning data are normally obtained through local planning agencies. Cross section and topographic mapping data are often available. Local agencies and local residents have some of the most valuable information to the engineer in their verbal and photographic descriptions of changes in the area over time, of channel changes from large flood events, of caving banks,of significant land use changes and when these changes occurred, of channel clearing/dredging operations, and other information. Newspapers and those who use the rivers and streams for their livelyhood are valuable sources of data.

CHAPTER 3

SEDIMENT YIELD

Section I. Introduction

3-1. Purpose and Scope. This chapter presents guidance on the selection and application of procedures for calculating sediment yield. Procedures are identified; positive and negative attributes of methods are presented in terms of the type of project for which the yield is needed; and important checkpoints in the use of the methods are presented. The sequence in which the methods are presented indicates the reliability of results, from most reliable to least reliable. This chapter does not describe all calculations in detail.

3-2. Need for Sediment Yield Studies. Soil erosion or soil loss is not the same as sediment yield. Eroded soil may be redeposited a few inches from where it was dislodged, whereas sediment yield from a basin is that portion of the eroded soil which leaves the basin. Approximately one-sixth of all eroded soil reaches the ocean during the time of significance to engineering projects. The determination of sediment yield normally is not the end product of a sediment analysis for projects in the Corps of Engineers. Rather, it is an intermediate step in broader studies of sedimentation for reservoir projects, local flood protection channel projects, navigation projects, alternative future land use studies, and the other projects in which the Corps engages. In almost every case the real need is to forecast future conditions, and yet the material presented herein focuses on hindcasting a historical period. That is because land use, rainfall, and runoff are known for hindcasting; therefore, attention can be directed toward the application of the technique. However, in forecasting future yields, all these parameters must be estimated. Moreover, hindcasting is the required technique for "confirming" that the procedure will be valid for the proposed study area. Finally, two different levels of forecasts are needed: one is the long-term average to provide results for project life and maintenance and the other is sediment yield for single events. Specific requirements vary from one type of project to another as illustrated in the following subparagraphs.

a. Reservoirs. Each reservoir project needs a sediment yield analysis, and most yield studies to date have been performed to calculate reservoir storage depletion resulting from the deposition of sediment during the "project life." The project life for a flood control reservoir is different from that of a navigation reservoir. Since total yield is probably 90 percent suspended sediment, the primary field data needed for reservoir sedimentation forecasts are the suspended sediment discharges. Those needs will continue into the future as reservoir use studies, such as the reallocation of storage, the modification of operating rules, and the preparation of periodic sedimentation reports, update and reevaluate sediment yield. Suspended sediment sampling equipment was perfected to obtain such field data. The field data for headwater reaches of reservoirs, on the other hand, should include total sediment yield by particle size because that is where the sands and gravels will deposit. Calculating the behavior of these coarse particles requires a more detailed data collection and analysis program than just the

suspended sediment concentration.

b. Local Flood Protection Channel Projects. Whereas reservoirs provide flood protection by modifying storage levees, diversions, and channelization are hydraulic means for reducing flood damages. Similarly, reservoir projects provide sediment storage, whereas sediment storage is typically not provided in channel projects except in special containments like debris basins. Consequently, problems resulting from sedimentation, both depositional and erosional, are noticed more frequently and earlier in the life of a channel project than they are at a reservoir. In addition, a reservoir acts as a sink, whereas a channel project creates both sinks and sources for sediment, and the most common problems are the deposition of sands and gravels or the erosion of sands and silts. So rather than total volume, sediment yield studies for channel projects must produce the volume of the bed material fractions. In most cases those are the particle sizes which are too large to be measured with suspended sediment samplers. Moreover, field samples of bed sediments must describe the sediment particle sizes "that will become the bed of the constructed project." Finally, sediment yield studies for a reservoir focus on the upstream watershed; whereas in channel projects they must also include the project area. A rigorous sediment yield forecast is required to produce such refinement.

c. Channel Projects for Navigation. Although the water-sediment behavior is similar to that in flood protection channels, the question being addressed is different. A flood project seeks to reduce the stage. A navigation project seeks to provide reliable water depth. The two are sometimes complementary and sometimes competitive requirements. The yield of sand is significant to both. Silt and clay are common materials dredged from navigation channels, whereas silts and clays are not common problems in flood channel studies, except in backwater and salinity areas. Another significant difference between the two channel uses is the resolution required to locate problem areas. Even one shallow crossing will obstruct navigation whereas that probably would not significantly change the stage of a flood.

d. Alternate Future Land Use Studies. Not only is future sediment yield important in project formulation but also it is important in land use planning even if no project is contemplated. The expanded flood plain management studies (XFPI's) have routinely identified areas of developing watersheds having high erosion potential and therefore significant sediment yield for receiving streams. Advance knowledge of yield potential can allow more intelligent land use decisions to be made. When a project is being considered, sediment studies should forecast a future condition without the project in place to establish how stream stability is changing through time as hydrology and sediment supply adjust to changes in land use, water chemistry, and other projects in the basin. As in hydrologic studies, a sediment investigation must establish the future conditions with project in place.

3-3. Field Reconnaissance. A reconnaissance of the stream should be conducted prior to adopting a method for calculating sediment yield because current methods do not aggregate erosion from the individual mechanisms eroding the sediment (i.e., sheet/rill erosion, gully erosion, bank caving, bed gradation, and tributary inflows). The field reconnaissance allows the

engineer to determine the main sources of sediment entering the project. He should use that information to select the most appropriate method or methods for the sediment yield analysis. For example, the Universal Soil Loss Equation is not appropriate for a small watershed exhibiting severe bank caving or gully erosion because that equation was designed for sheet and rill erosion. Therefore, a field presence cannot be overemphasized when determining sediment yield. If sedimentation is critical to the recommended alternative, a rigorous sediment yield analysis is recommended early in the project planning process.

3-4. Methods for Determining Sediment Yield. The large variety of sediment yield methods can be placed into two broad categories: methods based on direct measurement and mathematical methods. Only those based on direct field measurements are considered a rigorous approach; mathematical methods are trend indicators at best.

Section II. Sediment Yield Methods Based on Direct Measurements

3-5. Introduction. This grouping of sediment yield methods is based on direct measurements of hydrologic, hydraulic, and sediment parameters in the study area. There are three major subcategories as follows: in-stream sampling, reservoir sedimentation investigations, and regional analysis.

3-6. In-stream Sampling. Instream sampling techniques are documented in [21] and [64]. This is the most reliable approach, and the several methods presented in the following subparagraphs are listed in the order of preference.

a. Published Long-Term Daily Discharge Records. The most accurate historical sediment discharge is that calculated from a long-term sediment gage record. The standard procedure used by the US Geological Survey is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as illustrated in item [46]. These records usually express sediment concentrations in milligrams per liter, and those units can be converted to tons per day with the following equation:

$$Qs = 0.0027 * Q * C * k \tag{3-1}$$

where

Qs = sediment discharge, tons per day
0.0027 = convert cfs to tons/day/1000000 parts
Q = mean daily water discharge, cubic feet per second
C = mean daily sediment concentration, ppm
k = convert ppm to mg/l
k = 1 for concentrations less than 16000 ppm, otherwise See table 2 [46] or use the following equation.

$$k = \{10^{**}6 \ / \ [(10^{**}6)/(Cppm^{*}Sw) \ - 1 \ / \ Sw + 1 \ / \ Ss]\} \ / \ Cppm \qquad (3\text{-}2)$$

where

Ss = specific gravity of the sediment particles
Sw = specific gravity of the water

Usually, only the "measured load" is published; however, suspended samplers do not measure the lowest 0.3-0.4 feet of the water column. The sediment concentration in that "unmeasured zone" is usually estimated to be from 5 to 15 percent of the measured concentration, and that value is added to the suspended load to get the total. Before comparing sediment yield for one year to that for another, the period-of-record data should be examined for homogeneity. Adjustments for upstream reservoirs, the hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

b. Period Yield Sediment Load Accumulation. This is the technique used by the USGS to calculate monthly and annual suspended sediment yield after the long-term mean daily values have been computed. Summations use the average daily sediment discharges, but they can be hourly for smaller streams. Reaches of river downstream of a major reservoir which receive little tributary contribution, or reaches of major rivers where the discharge is fairly constant for long periods of time, could have yearly sediment yield computed by summation of monthly or weekly loads. The engineer is responsible for determining the proper time interval to use.

c. Flow-Duration Sediment-Discharge Rating Curve Method. This is a simple integration of the flow duration curve with the sediment discharge rating curve at the outflow point from the basin. It is the most common method used in the Corps of Engineers because:

- o both the flow duration curve and the sediment discharge rating curve are process-based and can be changed from the historical values needed for hindcasting to values needed for forecasting water and sediment runoff in the future;

- o and these curves can be scoped to reflect specific components of the sediment runoff process (i.e., a sediment discharge rating curve can be calculated for sand and gravels when those are the types of sediment of most interest to project performance).

The sediment discharge rating curve is sometimes called a suspended sediment transport graph or a suspended sediment transport relationship. It is a relationship between water discharge and sediment discharge as illustrated by Figure 3-1. The flow duration curve of mean daily water discharges at that same gage is illustrated in Figure 3-2.

(1) Calculations. The computation of yield starts by establishing computation points along the flow-duration curve. Select either class intervals of Q or intervals along the "percent of time flow was equaled or exceeded" axis. In the example which follows, shown on Table 3-1, the latter approach was used. The percent exceedance is tabulated at each ordinate,

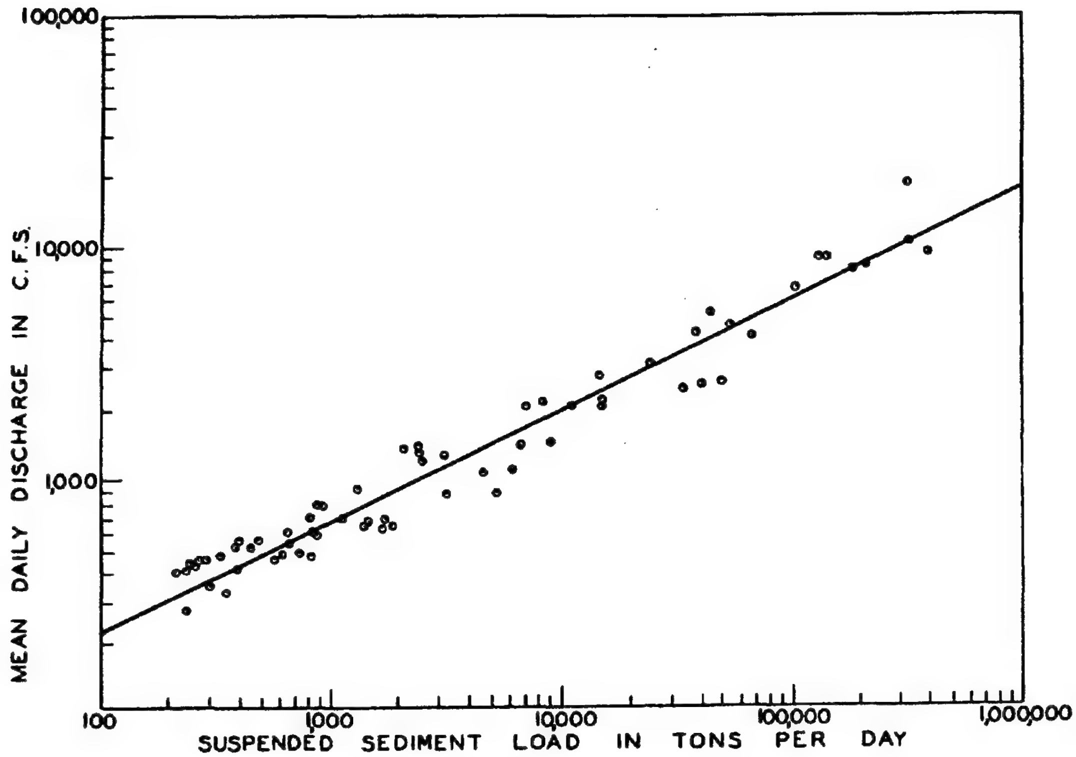


Figure 3-1. Sediment discharge rating curve, Elkhorn River, Waterloo, Nebraska

column 1, forming increments sufficiently small so the exceedance curve is approximated by straight line segments. The midpoint of each segment and its incremental time, in percent, are calculated in columns 2 and 3, respectively. Note, column 3 is referred to as having units of time because the units of the exceedance axis is time. The value of Q for the midpoint of each segment is recorded, column 4, and the sediment discharge for that Q is read from the sediment discharge curve and recorded in column 5. The daily average Q is calculated, column 6, by multiplying the water discharge by the time increment expressed as a decimal, column (4)x(3)/100, and summing all increments. The daily average sediment discharge is calculated similarly, by multiplying the suspended sediment load in column (5) by column (3)/100 and summing the column.

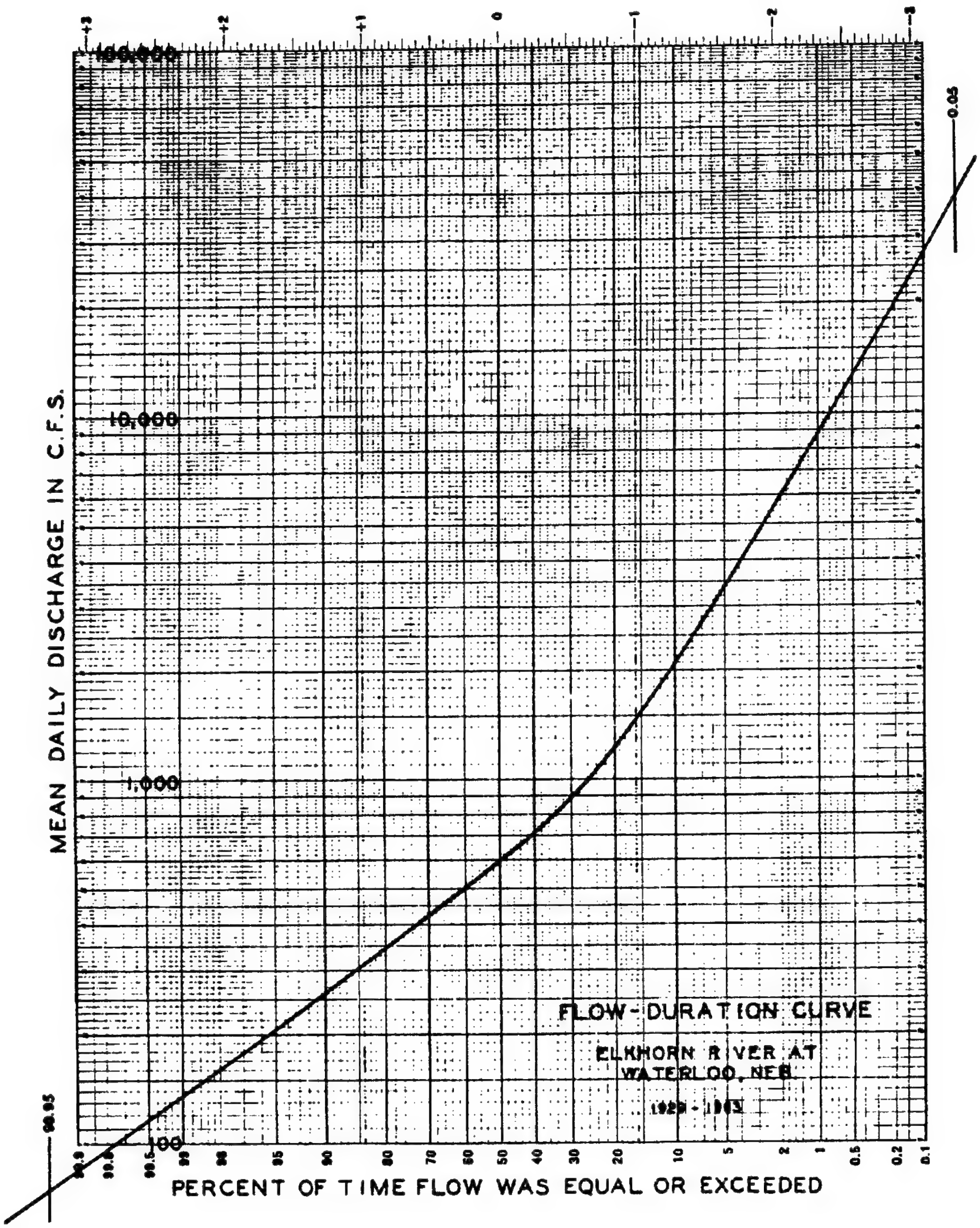


Figure 3-2. Flow duration curve, Elkhorn River, Waterloo, Nebraska

TABLE 3-1. Total Sediment Yield, Elkhorn River at Waterloo, Nebraska

Flow Duration in Percent Exceed-ence	Mid Ordinate	Incre-ment	Water Discharge Qw[1] (cfs)	Sediment Discharge Qs[2] (tons/day)	Daily Average Qw (cfs)	Daily Suspended Qs (tons/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0						
	0.05	0.1	37,000	4,500,000	37.0	4500
.1						
	0.3	0.4	15,000	680,000	60.0	2720
.5						
	1.0	1.0	9,000	230,000	90.0	2300
1.5						
	3.25	3.5	4,500	55,000	157.5	1925
5						
	10	10	2,100	11,000	210.0	1100
15						
	20	10	1,200	3,500	120.0	350
25						
	30	10	880	1,800	88.0	180
35						
	40	10	710	1,150	71.0	115
45						
	50	10	600	800	60.0	80
55						
	60	10	510	580	51.0	58
65						
	70	10	425	390	42.5	19
75						
	80	10	345	250	34.5	25
85						
	90	10	260	140	26.0	14
95						
	96.75	3.5	180	64	6.3	2
98.5						
	99.0	1.0	135	35	1.4	1
99.5						
	99.7	0.4	105	20	0.4	0
99.9						
	99.95	0.1	74	13	0.1	0
100					1055.7	13,409

Notes: [1] Stream Flow Record, 1929 to 1963
[2] Suspended Sediment Sampling Record, August 1948 to November 1950

The annual yield of water is the product of the mean daily value times 365 days per year times the conversion factor for acre-feet.

Annual Water Yield = 1055.7 x 365 x 1.98
= 762,950 acft/yr

The annual yield of suspended sediment is the product of the mean daily value times 365 days per year expressed in tons.

Annual Suspended Sediment Yield = 13,409 x 365
= 4,594,000 tons/yr

Assume the Unmeasured Sediment Discharge is 10% of the suspended discharge, 459,000 tons/yr, the resulting annual sediment yield is

Total sediment yield = 4,594,000 + 459,000
= 5,053,000 tons/yr

Total drainage area at the gage is 6,900 square miles of which the sediment contributing drainage area is 5,900 square miles.
The resulting annual unit sediment yield is

Unit sediment yield = 5,053,000 / 5900
= 856 tons/square mile

(2) Adjustments. Even when flow duration and sediment discharge curves are based on extensive field measurements, some adjustment may be necessary.

(a) The field data should be converted from instantaneous measurements of concentration into mean daily sediment discharges having units of tons per day. Values should be plotted versus mean daily water discharge on a log-log grid to form a suspended sediment discharge curve. To be considered as representative of long term conditions, samples should include a wide range of water discharges, flood sizes, land use changes and seasonal responses of the watershed.

(b) Estimates of the unmeasured load should be included to obtain the total sediment load as presented in the previous method.

(c) The flow duration curve is usually based on a longer record than that of the sediment discharge curve. Streams, particularly in arid regions, which transport the majority of sediment by one or two high-flow events each year may not have adequate discharge records in this range to estimate yield. In other cases new stations may not have experienced the flood flows. To fill in this crucial data may require some adjustment to the high-flow portion of the flow duration curve, statistically, to include extreme events which have been developed hydrologically. Another technique is to pattern the low-probability events after nearby gaged stations.

(d) The first step in forecasting future sediment yield is to estimate the future, sediment-discharge rating curve and the future flow-duration curve. Natural systems, i.e., climate and land form, are considered to be represented by historical records unless there is evidence to the contrary. Land use, on the other hand, is subject to man's activities and may change significantly during the life of a project. As a result both the flow

duration curve and the sediment discharge relationship may require adjustment. Once the future relationships are established, the calculation of water and sediment yields follows the same procedure as described for historical conditions.

(3) Points of Caution About the Flow-Duration Sediment Discharge Rating Curve Method.

(a) The sediment discharge rating curve is plotted as water discharge(Q) versus sediment discharge(Qs) on a log-log grid. However, the amount of scatter in such plots shows that sediment discharge is not a simple function of water discharge. Consequently, the engineer should investigate and evaluate any regional and watershed characteristics which might contribute to that scatter. For example, plot the water discharge in cfs versus the sediment concentration in ppm to avoid the dependency from having Q on both axes of the sediment discharge rating curve. Test for homogeneity with respect to season of the year, systematic changes in land use, type of sediment load, and type of erosive mechanisms. Use a multiple correlation approach coupled with good engineering judgement to establish the dominant factors influencing historical concentrations. Predict how those factors might change in the future and how such changes will impact sediment concentrations and particle sizes. An excellent discussion of the application of seasonal separation, and other causes of scatter in sediment discharge records, is given by [42].

(b) Note that for channel studies the bed material load is the most important contribution of the entire sediment yield since it is the one which deposits first and controls the behavior of the channel.

(c) The amount of wash load in the sediment influences the amount of scatter in the data because the amount of wash load depends on its availability and not upon hydraulics of flow. Also, as the concentration of fines increases above 10,000 ppm, the transport rate of sands and gravels is increased significantly as shown by [2].

(d) Water temperature causes a significant variation in transport capacity of the bed material load. When coupled with seasonal changes in land use, separate warm and cold weather sediment discharge rating curves may be required to achieve acceptable accuracy in the calculated results.

(e) Separate samples according to "population" for later analysis. For example, land surface erosion caused by sheet and rill processes is strongly correlated with rainfall impact energy. Therefore, the correlation of in-stream sediment concentrations with water discharge from rainfall-runoff, which has different erosive mechanisms than the snow melt-runoff process, may show an improvement when compared with the correlation of the entire data set. Likewise, the artificial floods, such as the pond break-out which occurred on the avalanche formed by the May 1980 eruption of Mt. St. Helens, will contain yet another population of erosive mechanisms and data from such events should be analyzed separately from both snowmelt and rainfall-runoff events.

(f) It is usually necessary to extrapolate the sediment discharge rating curve to water discharges well above the range of measured data. Exercise great care when doing so. Give first consideration to extrapolating concentrations, rather than sediment discharges. Include lines of constant concentration along with the measured data, i.e., C = 1000, 10,000, 100,000 and 1,000,000 ppm. The maximum possible concentration is 1 million ppm, which is solid rock. Be careful not to extrapolate into embarrassment. As the final step, convert the relationship back to a sediment discharge rating curve using equation (3-1).

(g) Extrapolating the relationship for total concentration does not guarantee the proper behavior of individual size classes. Check each one before accepting the results.

(h) It is possible to measure as much variation in concentration from one event to another as occurs from one discharge to another within a single event. Developing a concentration curve for a single event analysis must accommodate such a possibility. Therefore, fit two lines through the data. One should be the curve of best fit and the other should be the 95 % exceedance curve. Test the sensitivity of the project to sediment discharge by using both curves as the inflowing load.

(i) This method is considered to give a reliable estimate of sediment yield, but where historical values are available from long term records the results of this method should be checked against those values and the sediment rating curve adjusted, within the scatter of data, as required to reproduce the historical value.

(j) The western regions of the United States, which undergo pronounced wet and dry seasons, may require separate sediment rating curves for early rainy season events from those for the balance of the rainy season. This is important because aeolian mechanisms are particularly active during the dry season which leaves an abundance of erodible sediment for the beginning of the next wet season. As that supply is exhausted by early precipitation events, the runoff can shift from one having a very high concentration of sediment to one having a supply controlled by runoff energy. These differences can be expressed by using seasonal sediment discharge and flow duration curves.

d. Flood Water Sampling. When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is recommended early in the planning studies. Such short-record approaches are called flood water sampling.

(1) Calculations. Calculations are the same as described previously for the flow duration-sediment rating curve method.

(2) Adjustments. The same adjustments to flow and sediment concentration curves would be appropriate, but there is usually insufficient data to make them.

(3) Points of Caution About the Flood Water Sampling Method. The same points are appropriate that were discussed for the flow-duration sediment

discharge rating curve method. In addition, consider the following because the short record will not necessarily provide a representative sample.

(a) This yield should be regarded as less reliable than values determined by the flow-duration sediment discharge rating curve technique because the data may not be representative of the long-term sediment concentrations from the watershed. The absence of floods or the occurrence of one or two large events may biased the yield calculation.

(b) Since there is less confidence in yield estimates, sensitivity tests should be performed to evaluate the impact of shifts in the load curve on the alternative being analyzed. If doubling, or tripling, the sediment discharge does not greatly affect the alternative under study, additional sediment data may not be necessary.

(c) Since sediment discharge curves are often displayed as a straight line relationship logarithmically against discharge, and often with a slope of about 2, anticipation of that "rule-of-thumb" slope is comforting when working with a limited amount of measured data. However, in sand bed streams use sediment transport functions to curve-fit and extrapolate the sand discharge data. In gravel bed streams, sand behaves like wash load, but sediment transport functions are useful for curve fitting and extrapolating the gravel discharge.

(d) There is no rule of thumb, nor is there a transport function, for the amount of wash load in a stream. A correlation has been observed, at some locations, between the fraction of bed material present in the suspended sediment samples and the total concentration. If present, such a correlation allows the wash load to be extrapolated because the bed material discharge can be calculated using transport functions.

(e) Use a variety of methods when field data is inadequate. Always include sediment transport calculations for the sand and gravel loads. Consider using numerical models to fill in missing data by transposing existing records.

(f) Where a limited sampling program can be scheduled and funded prior to the start of detailed studies, this technique becomes quite valuable to supplement/modify the results of other methods. If a program was not possible during the feasibility report stage, one is strongly recommended for the design phase.

3-7. Reservoir Sedimentation Investigations. Many reservoirs across the United States, ranging from a few acres to thousands of square miles in drainage area, are periodically surveyed. The quantity of sediment deposited since the previous survey is calculated by subtraction. The results of these calculations are published in item [63], which is updated every 5 years. Storage changes and annual deposition in tons per square mile of drainage area are available. Since the volume of deposition is the sediment yield times the reservoir trap efficiency, sediment yield can be estimated provided a representative trap efficiency can be determined for the period between the surveys. This method for calculating sediment yield is considered by some

agencies to give the best estimate, although the inflow record during the time period between reservoir surveys should be carefully analyzed. That is, droughts or large floods can greatly bias the estimate. It is not unusual to have a large percentage of the total deposition occur during one or two large flood events. To detect such occurrences, plot the annual sediment yield relationship as shown in Figure 3-3. Consider the following factors when using the reservoir sedimentation survey technique to estimate sediment yield:

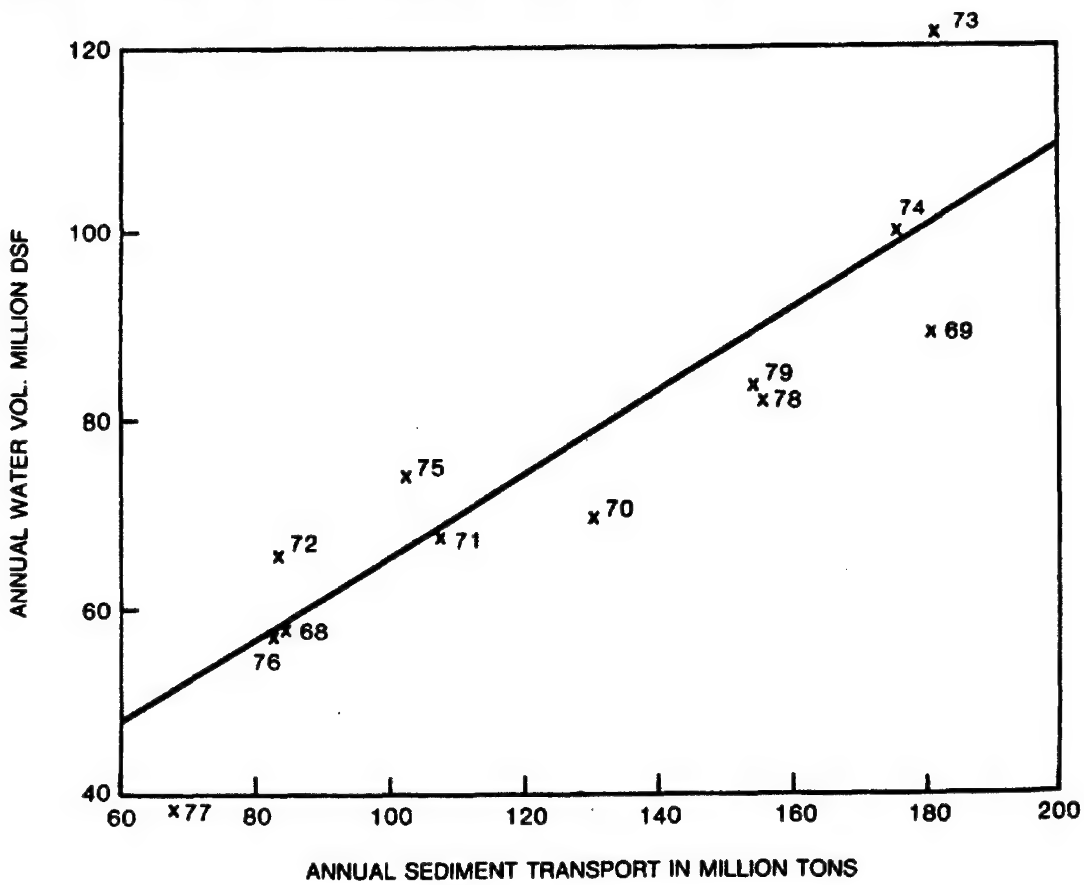


Figure 3-3. Sediment yield relationship

a. Trap Efficiency. Reservoir deposition is not synonymous with sediment yield. Some amount of inflowing sediment leaves the reservoir through the outlet and is not deposited within the pool. Although studies by Brune and others showed that reservoirs generally trap greater than 80 percent of the inflow, that should not be considered a rule-of-thumb. The reservoir trap efficiency must be determined and the measured deposit increased to account for that sediment passing through the reservoir. Trap efficiency is calculated by knowing the flow velocity through the reservoir and the gradation of the inflowing sediment load. Because flow velocities are difficult to estimate, Brune, item [10] proposed a surrogate means by which flow through time is related to the ratio of reservoir storage divided by average annual inflow. This relationship is widely used. Appendix F of this

manual describes trap efficiency calculations in detail.

(1) Dry Detention Structures. The trap efficiency of a dry detention storage area would be expected to be less than that in a permanent pool reservoir. However, investigations of several small reservoirs, reported by Dendy item [16], have shown little difference in deposition between the two types of reservoirs. Trap efficiency relationships appear to apply equally well for both a permanent pool or dry reservoir, although the dry reservoirs in Dendy's study had only a 5-year maximum length of record. In calculating sediment yield for an existing dry detention structure, allow for some scouring and removal of previously deposited material during times of low to moderate in-channel flow through the reservoir area. Although no specific guidelines are available, Soil Conservation Service(SCS) techniques utilizing the Brune curves have incorporated a further adjustment for estimating yield from watersheds draining into dry detention areas. SCS employs a decrease in calculated sediment trap efficiency of 5 percent for streams that have incoming sediment consisting primarily of sand and a decrease of 10 percent for streams which carry predominantly fine material (silts and clays).

(2) Run of River Structures. Unlike dry detention or permanent pool reservoirs, run-of-river structures are not designed for flood storage but to maintain a minimum depth for navigation. Consequently deposition within the navigation pool is much less than within a flood-control reservoir, primarily occurring during normal flow periods. During flood periods, when the gates of the navigation dams are open and the river profile is about the same as the pre-project profile, some erosion of the previously deposited material may occur. Although primarily empirical, two techniques for estimating trap efficiency in a run-of-river pool are briefly described in Appendix C. It is more likely, however, that a computer model, such as HEC-6, would be needed to determine trap efficiency by calculating depositional changes in a navigation pool from year to year. Results from a period-of-record computer simulation could be used then to determine yield at the structure.

(3) Debris Basins. Debris basins are a special case of the dry reservoir designed to retain the coarsest sediments. The volume and rate of clean out are monitored, but it is extremely difficult to estimate total sediment inflow because trap efficiency typically changes drastically as the basin fills. Short circuits and high concentrations of fines are common; and trap efficiency is very sensitive to grain size. All of these complicate the use of debris basins in defining sediment yield from the watershed. The best approach is to process the system using a numerical model and calibrate the inflowing sediment discharge rating curve so the model reconstitutes the historical volume of sediment removed from the debris basin.

b. Sediment Size. The amount of sediment trapped by a reservoir or a debris basin depends on the flow velocity, flow depth, and sediment particle sizes. With the possible exception of dry detention areas or pondlike structures, it is reasonable to assume the trap efficiency of inflowing sands (particle sizes greater than 0.125 mm) to be 100 percent. Silts and clays are more difficult to settle, but pools with as small a ratio as 0.1 of reservoir capacity to average annual inflow settle 80-95 percent of all sediments.

c. Settling Velocity of Sediment Particles. Specific methods of computing settling velocities for sediment materials of various sizes and types are described in item [2] . This method is computerized in the CORPS system. The time required for sediment particles to settle out of the water column relative to the time required for flow to pass through the reservoir is a check against empirical trap efficiencies.

d. Consolidation of Deposition. Analysis of sediment yield from reservoir deposition requires a conversion of the deposited material from a volume per year basis to a weight per year basis. Deposited material in the pool contains varying amounts of water within its voids. This water volume changes with time as the deposition is consolidated. This consolidation must be considered in the yield calculation. Corps guidelines in developing these specific weights of deposited material are largely taken from item [2].

e. Contributing Drainage Area. The measured reservoir deposition must be adjusted for the actual contributing drainage area to obtain the correct sediment yield. The pool area should be deleted from the overall drainage area as should all other drainage areas controlled by reservoirs. In many parts of the country, portions of the watershed can be nondraining, with runoff going to potholes or sinkholes, or the soil may be primarily coarse material that allows little if any runoff. These areas may also be considered for deletion from the overall drainage area. Major changes in the upstream watershed between reservoir survey periods (extensive channelization, upstream reservoirs coming on-line, and other factors) should be accounted for during the development of unit sediment yield.

f. Erosion Mechanism. Relating sediment yield to drainage area assumes the primary erosion mechanisms are sheet and rill erosion. That may be true for silt and clay sediment, but the most likely erosion mechanisms for sands and gravels are gullying, bank erosion, and bed degradation. "Miles of channel having erodible bed and banks" is a better correlation parameter than drainage area for these mechanisms. Aerial photography is the best data source. In the more extreme cases, mass wasting mechanisms such as land slides or debris flows provides large volumes of all sizes of sediment.

3-8. <u>Transfer of In-Stream Data.</u> A wide variation in sediment discharge curves will be seen at different locations along a stream because minor changes in velocity will produce a significant change in the sediment transported. Therefore, transfer of sediment discharge rating curves from one point in a watershed to another point is discouraged. However, converting the discharge curve data to an annual sediment yield curve will usually result in a consistent relationship with drainage area, when land use, topography, and soils are similar. A plot of annual sediment transported against annual discharge can be used to estimate yield at different locations using the technique presented in the next paragraph.

3-9. <u>Transfer of Reservoir Deposition Data.</u> Sediment yield data calculated at a specific reservoir site can be transferred to the study watershed provided the topography, soils, and land use, particularly the percentage of both basins in agricultural usage are similar. If these similarities exist, transfer can be made by SCS techniques described in item [62] , or other

criteria. SCS uses the following practices in transferring reservoir data east of the Rocky Mountains:

> Direct transfer for study watersheds greater than 0.5 or less than 2.0 times the drainage area of the reservoir surveyed area.
>
> No transfer for study watershed less than 0.1 or greater than 10.0 times the drainage area of the reservoir surveyed area.
>
> Application of the following equation for study watersheds within these boundary limits:

$$Ye = Ym\ (Ae/Am)**0.8 \tag{3-3}$$

where

- Ye = the total annual sediment yield estimated for the area under study, tons/year
- Ym = the total annual sediment yield measured at the reservoir site, tons/year
- Ae = the contributing drainage area for the site estimate
- Am = the contributing drainage area for the reservoir measurement

These guides do not apply to mountainous areas which often show no consistent change in sediment yield for change in drainage area, or to streams where channel erosion may increase the sediment yield per unit area relationship with increasing drainage area.

3-10. Regional Analysis. Regional analyses have been performed for some areas of the United States and sediment yield is shown on maps, by graphs, or with equations based on definable parameters. However, regional methods should not be the only techniques used to calculate sediment yield. They are acceptable as preliminary procedures and are suggested as alternatives to support the other, more detailed, methods. In choosing a regional method always justify that their regression parameters include the erosive mechanisms that are predominant in your particular area of the region. That is, drainage area is an adequate parameter for land surface erosion, but it should not be correlated with stream bank erosion or even gullying. If these latter two are the predominate erosive mechanisms in your specific problem area of the region, avoid a regional equation that only includes drainage area. A few regional methods are:

a. Dendy and Bolton Method. This equation for sediment yield, developed by [17], has the widest potential application in the United States. Sediment yield from about 800 reservoirs throughout the continental United States was related to drainage area and mean annual runoff by the following two regression equations.

For watersheds having a mean annual water runoff equal to or less than 2 inches:

$$S = 1280 * (Q**0.46) * (1.43 - 0.26 \log A) \qquad (3\text{-}4)$$

For watersheds having a mean annual water runoff greater than 2 inches:

$$S = 1958 * [e**(0.055 * Q)] * (1.43 - 0.26 \log A) \qquad (3\text{-}5)$$

where

- S = Unit sediment yield for the watershed, tons per square mile per year
- Q = Mean annual water runoff for the watershed, inches
- A = Watershed area, square miles
- e = 2.73

Since these equations were developed from average values of grouped data, they are appropriate for general estimates. A better estimate can be expected for the larger, more varied watersheds than for smaller site specific areas. Do not use these equations for mountainous areas.

b. Pacific Southwest Interagency Committee (PSIAC) Method. The PSIAC method item [44] was developed for planning purposes and is applicable for basins in the western United States greater than 10 square miles. Sediment yield is directly proportional to the total of the numerical values assigned to nine different factors: land use, channel erosion/sediment transport, runoff, geology, topography, upland erosion, soils, ground cover, and climate. Numerical values range from 25 to -10 for each factor. Sediment yield can range from 0.15 acre-feet per square mile per year for watersheds with low PSIAC factor (20) to more than 3 acre-feet per square mile per year for large factors (100 or more). The PSIAC technique has compared well with actual watershed data and is one of the few methods which can estimate changed sediment yield caused by local land use management changes.

c. Tatum Method for Southern California. The Tatum method item [50] is used to calculate sediment yield and debris volumes for the arid, brush-covered, mountainous areas of southern California, see Appendix C. Calculations are made from nomographs using an equation with adjustment factors for size, shape, and slope of the drainage area, 3-hour precipitation, the portion of the drainage area burned, and the years occurring between the time of the burn and the time of the flood.

d. Transportation Research Board Method. Current guidance on the design of sediment-debris basins is given in [53]. Estimating sediment yield is one of the tasks in that design guidance.

e. Other Regional Studies. Several other regional approaches are available for estimating sediment yield. Appendix C describes methods by Mack item [40], Hill item [29], and Livesey item [39] . In addition, site specific

studies, conducted by the Corps of Engineers, other Federal agencies, state agencies, universities, drainage districts, planning units, and other commissions and groups, may offer valuable sources of regional information for sediment yield. The engineer should perform a thorough literature search to determine what information may be available for the area under analysis.

f. Basin Specific Regionalization. Most of the regional criteria available for sediment yield are applicable over a wide area, and may not give an acceptable yield estimate for a specific watershed within the region. Consider applying the regional concepts described above to the specific watershed of the problem area. This type study could significantly improve the accuracy of yield calculations as compared to those obtained from the generalized criteria. Procedures for performing regional studies are described in item [22].

Section III. Mathematical Methods for Calculating Sediment Yield

3-11. General. The second major grouping of methods for calculating sediment yield are mathematical methods --the application of analytical techniques to calculate sediment yield from watershed, based on sediment and hydraulic parameters. The several techniques are placed into four categories: sediment transport functions, soil loss equations for small watersheds, bank/gully erosion, and watershed models. These methods were developed because sediment yields are needed at locations where there are no direct field measurement, and these methods can estimate sediment yield at a specific point without addressing the movement of sediment from point to point within the system. Most sediment yield studies utilize mathematical methods supplemented by whatever actual data are available. The results are not as reliable as the direct measurement methods presented in the previous section, and when sedimentation is a major project concern, a sampling station should be established in the project area to refine estimates made with the techniques presented in this section. Sole reliance on these mathematical methods to provide quantitative estimates of sediment yield would be unusual for a Corps analysis and would require careful justification in supporting the results. These methods are not listed in order of reliability.

3-12. Sediment Transport Functions. When sediment yield is needed for a site that has water discharge data but no sediment data, it is better to calculate a value using a calculated sediment discharge rating curve than to abort the effort altogether. A sediment transport function is the basis for the calculation. It can be used to calculate the bed material portion of the sediment discharge rating curve. Then the Flow-Duration Sediment-Discharge Rating Curve Method can be used to calculate the average annual yield of the bed material load. In channel studies this result will provide the most critical portion of the sediment load. That result is not adequate for reservoir studies, but it can be coupled with regional or mathematical techniques to calculate the wash load. Numerous sediment transport equations have been programed [66]. Please refer to reference [2] if more detail is needed. In addition, the HEC training document [26] describes a procedure for calculating the sediment discharge rating curve using the numerical sedimentation model HEC-6 [24]. That procedure differs from the application of a sediment transport function at a point in that HEC-6 integrates processes

over several cross sections which describe a reach of the river and provides a continuity equation for sediment movement. Consequently, it will produce a more reliable result than comes from applying a sediment transport function at a single point.

3-13. Universal Soil Loss Equation (USLE). Soil loss equations, evolving since 1940, have been developed for use in small, rural upland watersheds. The USLE is one of the most recent and most widely used of these equations. It was developed to predict the long-term average soil loss from agricultural land. Rainfall simulators were used to create the erosive energy. Test were conducted on plots which were 72 feet long on uniform slopes. Surface erosion occurred in the form of rills; the quantity of eroded soil was measured at the outflow point and expressed as tons per acre per year. Consequently, the uses of the USLE are quite limited for Corps projects. Reconnaissance studies could find the USLE with a sediment delivery ratio appropriate for a preliminary estimate of sediment storage for a small reservoir where sediment is expected to come from the watershed and is not expected to be a significant problem. The pertinent parameters were assembled into the following regression equation by Wischmeier and Smith [68].

$$A = R*K*L*S*C*P \tag{3-6}$$

where

A = Soil loss per unit area per time period, tons per acre per year
R = Rainfall erosion index
K = Soil erodibility factor
L = Slope-length factor
S = Slope-steepness factor
C = Cover and management factor
P = Support practice factor

a. Calculations. A value is estimated for each of these variables using information gained through a field reconnaissance of the watershed to enter tables and nomographs provided in reference [68]. SCS personnel should be consulted to ensure that appropriate values have been selected. Guidance on adapting the equation to incorporate the effects of thaw, snowmelt, and irrigation on the area, on estimating erosion from construction sites; and on modification of the R-value to estimate sediment yield on a frequency basis through the 20-year recurrence interval event for individual hypothetical storms is presented in reference [68].

b. Points of Caution When Using the USLE. The following points are made to stress proper use of the USLE.

(1) Channel Projects. The USLE gives no information on gradation of the eroded sediment. Consequently, the equations would be of limited value in analyzing the effects of a channel project where sands and gravels are of primary interest.

(2) Construction Sites. The significance of selecting coefficients can be illustrated by looking at the soil erodibility factor, K. Published coefficients for crop land imply regular tillage of the soil, and that disturbs the natural armor layer which forms during rain events. The significance of this, the soil erodibility factor, K, for a construction site is not the same as published for crop land in the USLE manual. Soil in a construction area would be expected to exhibit similar erosion to agricultural land during the first rain event after the ground was disturbed, but successive rainfall events would erode that soil at a reduced rate because the construction site is not plowed regularly.

(3) Erosion Mechanisms. The channelization of surface water runoff due to construction may increase gully and channel erosion significantly, and the USLE would miss that altogether because it is formulated for sheet and rill erosion.

(4) Sediment Transport. There is no transport function in the USLE, and a watershed sediment delivery ratio must be applied to account for overland deposition. However, the validity of results is questionable when the USLE is applied to subareas in excess of a few square miles.

3-14. Sediment Delivery Ratio. With the addition of a sediment delivery ratio (SDR), the USLE can be extended to areas of several square miles. The SDR is a factor, ranging from 0 to 1, to multiply times the annual soil loss to obtain the annual sediment yield for the watershed. Sediment delivery ratios have been calculated for specific areas, but no generalized equations or techniques are yet available to universally determine a sediment delivery ratio. The SDR is proportional to drainage area, and the available data indicates the ratio may vary with the 0.2 power, in the form of:

$$(SDR2 / SDR1) = (A1 / A2)^{0.2} \tag{3-7}$$

where:

A1 = reference drainage area, square miles
A2 = desired drainage area, square miles
SDR1 = sediment delivery ratio for reference drainage area
SDR2 = desired sediment delivery ratio

Vanoni item [2] suggests using a reference drainage area of .001 and a SDR1 of 1.0 in this equation. Figure 3-4 illustrates sediment delivery ratio-drainage area relationships for different regions in the United States, and Figure 3-5 shows a generalized relationship drawn through a mass of data points from various regions. Any arbitrary sediment delivery ratio selected solely on the basis of drainage area could be in considerable error; other factors (soil moisture, channel density, land use, conservation treatment, soil type, rainfall intensity, topographic relief, and so forth) must also affect the SDR in some manner.

3-15. Modified Universal Soil Loss Equation (MUSLE). The Universal Soil Loss Equation was modified by Williams [69] with the resulting equation termed the Modified USLE (MUSLE). The MUSLE allows the estimation of soil losses for each precipitation event throughout the year, thereby becoming an event model

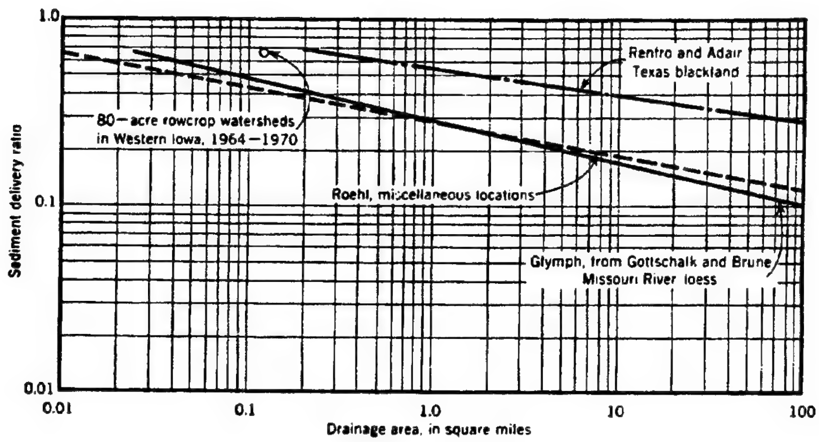


Figure 3-4. Sediment delivery ratios calculated for various watersheds (from item 2, Appendix A, courtesy of The American Society of Civil Engineers)

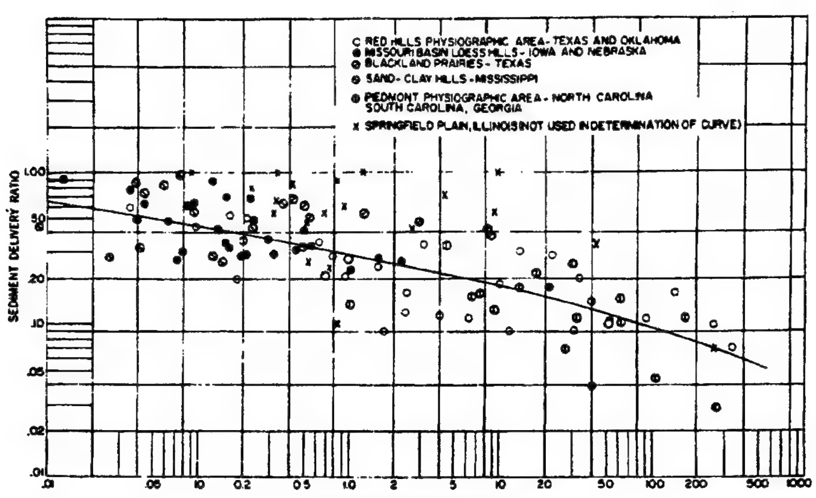


Figure 3-5. Example of scatter in the data (from item 2, Appendix A, courtesy of The American Society of Civil Engineers)

rather than an average annual runoff model. As an event model, the MUSLE and similar techniques have more application to Corps analyses. The full equation defining the MUSLE is:

$$Y = 95 * ([Q * qp]**0.56) *K*C*P*L*S \tag{3-8}$$

where

Y - Sediment yield from an individual storm through sheet and rill erosion only, tons
Q - Storm runoff volume in ac-ft
qp - Peak runoff rate in cubic feet per second
L*S - Slope length and gradient factor
K, C, P - as defined previously for the USLE

The MUSLE is simply the USLE with the rainfall erosion index replaced by the runoff rate term. Since erosion is computed for each event, a SDR is not necessary. The "Q" and "qp" terms would be obtained from the runoff hydrograph with "Q" used in estimating the amount of soil detachment and "qp" used in determining the volume of soil transported. The sediment yield for each event is summed to obtain each year's total with average annual sediment yield being the average of all the yearly values. Long-term simulation is normally required to obtain a representative estimate. While much additional information is gained from the use of the MUSLE and the necessity of determining an appropriate sediment delivery ratio is eliminated, this technique requires considerable data gathering and calibration effort to apply correctly. Reference [23] includes this method in the evaluation of potential deposition problems in a proposed flood control channel. The points of caution given for USLE apply to MUSLE also.

a. Runoff. A separate rainfall runoff model is needed to calculate flood volume and flood peak runoff rate. Calibration is usually against measured water volume, with at least 3 years of data normally needed.

b. Confirmation. Comparison and confirmation of sediment yield calculated with MUSLE should be made against that from other techniques. A report by Dyhouse item [18] describes a study in which sediment yield, which had been calculated by a method similar to the MUSLE, was calibrated using a flow-duration sediment transport integration.

3-16. <u>Gully and Stream Bank Erosion.</u> When the drainage basin exhibits extensive stream bank erosion and gullying, either on the primary stream or on tributaries to it, sediment yield determined by the following methods should be added to the sheet and rill erosion predicted by the soil loss equations.

a. Stream Bank Erosion. Soil losses through stream bank erosion and bank caving contribute significant quantities of the total sediment yield for most natural rivers. Estimates as high as 1,700 tons/year/mile of bank have been made at some locations. The causes are many and varied, and the prediction of future losses at specific locations is difficult. No generalized analytical procedures have yet been developed to formally calculate sediment yield or specific bank line losses from stream bank erosion. The most successful methods are based on aerial photography in which successive overflights can be

used to overlay bank line movement with time. By measuring the surface area between successive bank lines and estimating bank heights from the field reconnaissance, quantities of sediment lost to erosion can be calculated between the surveys and average annual rates determined.

b. Gully Erosion. Soil loss from gullies is seldom sufficient to warrant inclusion in Corps studies because it makes up a very small percentage of the total sediment yield when the study area is more than 10 square miles. However, some parts of the country, such as much of the State of Mississippi, experience major sediment losses from gullying. When significant gully erosion is suspected, contact the local Soil Conservation Service office for their estimates. Items [45] and [60] should be reviewed.

c. Future Conditions. When the future includes watershed modifications such as reservoirs, channelization or land use change, do not accept historical bank caving or gullying quantities without justification. Based on knowledge of river morphology and the reaction of rivers to man's activities nation wide, an assessment of the likelyhood of changes in historical values should be made.

3-17. Computer Models of Watershed Sedimentation. Extensive research is under way on these methods. In concept, the computer is used to simulate water movement and the associated processes of sediment erosion, transportation and deposition, throughout the watershed. Most are hydrologic models with sediment runoff capability added through soil loss equations. They require substantial data but have the advantage of predicting the effects of future land use changes in considerable detail. The Corps STORM model is an example of a watershed model with a capability for calculating sediment yield. It has been generally applied to watersheds of 10 square miles or less, about the maximum area for application of soil loss equations. More sophisticated watershed models which attempt to address the actual mechanics of erosion and sediment movement are being developed and used, however, these models are largely applicable to basins of a few square miles or less in size. Given the usual lack of sediment data, yield estimates by watershed computer modeling may not be as reliable as the more simplified techniques.

Section IV. Urban Sediment Yield

3-18. Urban Sediment Yield. The analysis of sediment yield for urban areas or for a watershed undergoing urbanization introduces still more complexities into an already difficult problem. Measured yield data is essentially nonexistent for urban watersheds. As previously noted, yield varies dramatically as land use changes. Removal of vegetation and disturbing the soil preparatory to development can increase sediment runoff by orders of magnitude during the construction process. However, as the developed land is restabilized the attention that property owners give to their land and the large increase in impervious areas (roads, structures, parking lots) with the resulting decrease in land surface area exposed to the erosive effects of rainfall and runoff will reduce sediment yield from land surface erosion to smaller values than existed on the preurban land use, as illustrated in Figure 3-6. The usual hydrologic effects of urbanization, increased runoff and higher flow peaks, may somewhat offset this decrease from land surface erosion

by increasing gully and channel erosion. All these factors are difficult to quantify.

3-19. Urban Yield Methods. Urban sediment yield methods are largely yet to be developed, however any of the methods previously described could be used. In practice, given the almost total lack of measured sediment data, yield methods have been limited to the various predictive techniques described in Section III. If discharge-duration data can be calculated for a prescribed land use, as by period-of-record hydrologic simulation, a transport equation can be calculated and integrated with that duration curve to estimate average annual sediment yield of the bed material load. A different land use would require a repetition of these steps after both the discharge-duration and sediment discharge curves have been modified to reflect the new land use condition. Mathematical modeling of the watershed's sediment runoff processes would normally be necessary to simulate flow duration data or to obtain sediment wash off information. Most soil erosion models have been developed for rural watersheds and rely on some variation of the USLE to calculate sediment runoff. Thus, parameter estimates in urban areas may reflect only the best judgment of the practicing engineer.

3-20. Adjustment Factors for Urbanization. Even with the problems involved with urban sedimentation analysis, proper evaluation for Corps work proposed in urban areas may still require an analysis of sediment yield under alternate land uses. The modification of a watershed's hydrology by urbanization has been much studied and can be analyzed by a variety of hydrologic models. The hydrologic effects of urbanization are generally shown as increased runoff volume from increased imperviousness factors and higher discharges from decreased overland and stream travel time. Most hydrologic models, however, do not simulate sediment runoff. Use of an appropriate sediment routing model under different land uses can at least allow qualitative estimates of the changes in sediment runoff, however subjective the selection of the various parameters might be. The summation of sediment runoff from individual events throughout the course of a year, along with summation of runoff water volume, will allow annual yield curves to be plotted. Figure 3-6 illustrates the calculated annual sediment yield for 20 years of water and sediment runoff simulation for two land use patterns using the HEC's STORM program item [25]. Average annual sediment yield can be found from summing and averaging the annual values. These yield curves can form the basis for adjusting a sediment discharge curve to reflect an alternative land use condition. Figure 3-7 shows the adjusted sediment discharge curve for a future land use pattern based on proportioning the "known" (existing land use) sediment discharge curve by the difference in the annual yield curves. Appendix C illustrates another method for estimating changes in sediment yield during urbanization. It is based on land use projections, available sediment yield data and urban runoff measurements.

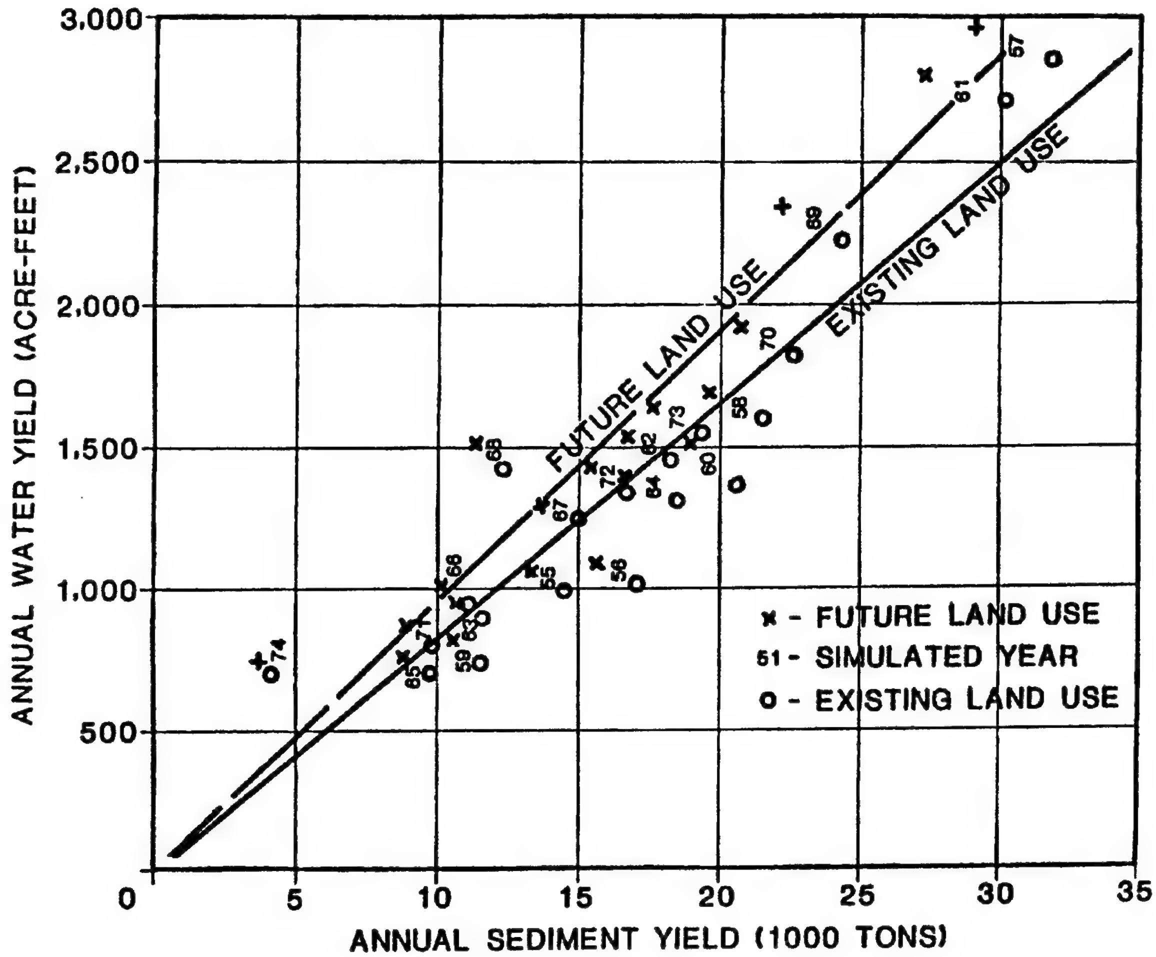


Figure 3-6. Effect of urbanization on sediment yield

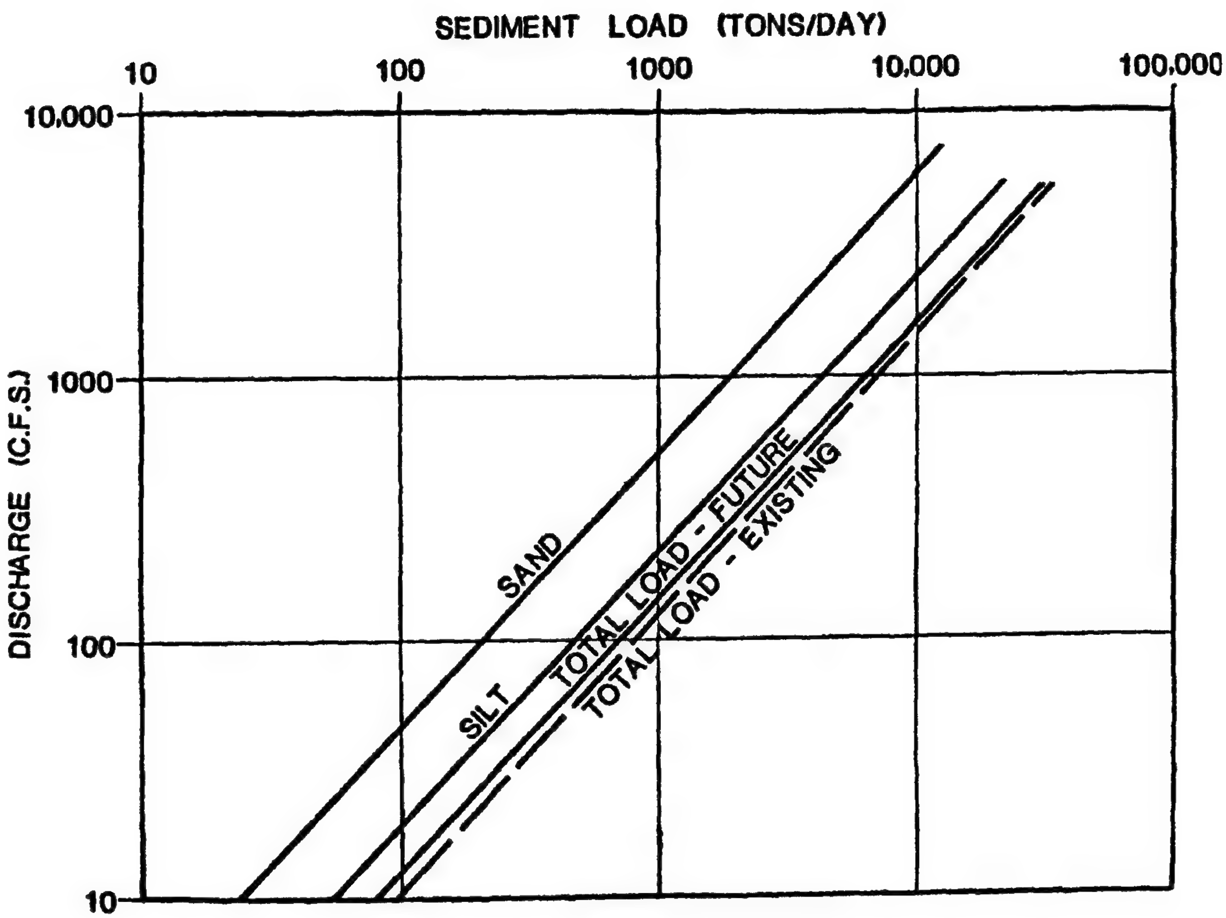


Figure 3-7. Sediment discharge adjusted for urbanization

Section V. Report Requirements

3-21. Topics to Report. Specific requirements necessary for every sediment report cannot be given, and reporting information necessary for sediment yield will be included with that requires for the entire sedimentation analysis. Information should include the level of effort used by the engineer to estimate sediment yield (qualitative vs. quantitative), references for techniques/technical data used, the method(s) used to calculate and check the adopted values for sediment yield throughout the study area. While additional reporting information is given in the following chapters, reviewers expect the following to be discussed or included:

a. Basin and study area map

b. Stream profile showing bed elevation versus river miles, hydraulic controls, structures, distributaries and tributary entry points

c. Land use map for study area

d. Soil type map for study area

e. Graph showing drainage area versus river mile

f. Graph showing average annual water yield versus river mile

g. Water yield

(1) average annual water yield by sub-basins including trends with time

(2) flow-duration curve (i.e. cumulative distribution function for water)

h. Water discharge hydrographs

(1) period of record

(2) single event (actual and/or hypothetical)

i. Water discharge versus sediment discharge rating curves, for the main stem as well as tributaries, showing measured data points

j. Sediment yield

(1) average annual sediment yield be sub-basin including trends with time

(2) fraction of average annual sediment yield carried by specific ranges of water discharge, Y versus Q-class interval (probability density function)

k. Graph of annual water yield versus annual sediment yield showing years (Figure 3-6)

l. Sediment yield for single events, actual and/or hypothetical

m. Sediment yield for clay, silt, sand, and gravel

n. sediment yield by grain size class (i.e., VFS, FS, MS, CS, VCS, etc.)

o. Sediment budget analysis for future conditions, with and without the proposed project

CHAPTER 4

RIVER SEDIMENTATION

Section I. Introduction

4-1. Purpose. The purpose of this chapter is to identify potential river sedimentation problems, to associate those problems with project purposes, and to propose approaches for analyzing them.

4-2. Scope. This chapter points out potential problems, offers guidance in selecting methods for their analysis, and cites available references for details in the field of Sedimentation Engineering. The scope of this chapter includes topics which were selected because of known problems and not for completeness of scientific knowledge. The thought processes for diagnosing sedimentation problems are given in an effort to separate the problems from the symptoms one sees in the field. Sedimentation problems associated with flood channels, navigation channels and permitting are presented in detail because of the mission of the Corps of Engineers; however, the concepts in this manual are not restricted to use in those problem areas. The steps required for conducting river sedimentation investigations are listed, and data requirements are itemized. Maintenance requirements are emphasized.

4-3. Philosophy of the Sedimentation Investigation. The two aspects of the investigation are

a. the impact of sedimentation on project performance, and

b. the impact of the project on stream system morphology.

The impact of the project on stream system morphology should not be determined by comparing a static condition of the stream system, as depicted by either current or historical behavior, to a "future condition with the proposed project in operation". A more appropriate measure of impact is to compare the "stream system with project" to a "future base condition." The future base condition is determined by forecasting the stream system without the proposed project, i.e., a "no-action condition." The "with project forecast" is made for a period equal to the project life. The "no-action forecast" should be made for the same period of time and should contain all future changes in land use, water yield, sediment yield, stream hydraulics and basin hydrology except those associated with the proposed project.

Section II. Evaluation of the No-Action Condition

4-4. Regime of the Natural River. Natural stream characteristics are the result of "natural forces" interacting with "natural resistances" so "natural changes" occur in a very systematic way. However, because the natural forces are not constant with respect to time and the natural resistances are heterogenous in both time and space, the natural changes contain fluctuations which require careful attention and investigation because they are difficult to understand and predict.

a. Stream Characteristics. "Stream characteristics" refer to channel dimensions, roughness, plan-form and position on the flood plain. In this document a natural river channel is considered to have six degrees of freedom: width, depth, slope, hydraulic roughness, plan-form and lateral movement of the channel bank.

b. Natural Changes. The term "natural changes" refers to the day in day out processes of bar building, bank erosion, lateral shifts of the thalweg alignment, aggradation of the channel bed, and degradation of the channel bed. These changes occur naturally whether man is present or not, but man's activities can accelerate as well as decelerate or completely reverse the behavior of the natural, dynamic stream system.

c. Natural Forces. Natural forces being imposed on a river system are the inflowing water discharge hydrograph, the inflowing sediment concentration hydrograph, the inflowing particle sizes in the sediment concentration hydrograph, and the downstream water surface elevations. These are imposed forces in that a reach of stream channel is being "loaded" by water and sediment from outside the reach. It can be from the upstream reach, from local runoff, or from tributaries. In addition to the inflowing conditions, there is the downstream stage hydrograph. It is a loading parameter in subcritical flow because the downstream stage controls the rate of energy dissipation in the reach. The tailwater can be a friction or contraction control; it can be another river, a lake or the ocean; or it can be a regulated boundary condition like a reservoir. There will be occasional geotechnical failures land slides which load the channel with sediment, but those are not associated with river hydraulic processes and, therefore, are not discussed in this manual. Floating debris is not considered a "natural force" in this manual, but it can severely impact the behavior of a stream channel.

d. Dependent Variables. In this manual the dependent variables are considered to be the six degrees of freedom presented in the paragraph, "stream characteristics." The independent variables are the natural forces - the imposed forces, discussed in the previous paragraph. The end product of a sedimentation investigation is the predicted reaction of each of those dependent variables in each reach of the channel to the aggregate of forces from the independent variables. The behavior of each reach depends on the reaction of the reach just upstream from it. This interaction is referred to as the "stream system concept." The concept of independent and dependent variables also suggests that one should not expect a constructed channel to perform without maintenance unless there is a corresponding change in the forces being imposed on the system.

e. System Behavior. Although the complete theory is not yet available, empiricism suggests that the six degrees of freedom change in system-like fashion as each reach of the river responds to the load being placed upon it from the upstream reach, from tributaries and from lateral inflows. Likewise, a reach of the river will modify the inflowing loads and pass a slightly different set of loadings to the next reach downstream. The concept of changes occurring with time is an important one. Rather than studying streams at only one fixed point in time, the engineer must view the stream system as

one of dynamic equilibrium in which channel width, depth, slope, bed roughness and alignment are continually changing.

4-5. Symptoms of Channel Instability in the Project Area. For a given project the identification of the study requirements begins by defining the boundary around the project area and the boundary around the study area. Classifying historical trends of channel behavior within that boundary, during the engineering time scale not geologic time, is one method for assessing the stability of the preproject channel. The criteria for performing such an analysis for channel design can be built around the six degrees of freedom of river behavior. Fluctuations in those values are normal, however, trends to change from one regime to another over time suggests channel instability. It would not be safe to use the present river as the model for a stable channel when such trends are present. Therefore, a more detailed analysis should be made.

4-6. Natural Sedimentation Processes. When forecasting the future base condition of the stream system, strive to quantify the following:

a. location and rate of bank erosion,

b. location and rate of bed erosion,

c. location and rate of deposition,

d. lowering or raising the base-level of the stream system water surface elevations,

e. channel width, depth and slope,

f. turbidity,

g. water quality aspects of sedimentation,

h. shifting location of deep-water channels,

i. head-cutting of the approach channel,

j. head-cutting up tributaries,

k. aggradation of the exit channel, and

l. local scour at bridges and hydraulic structures.

These problem areas are not an exhaustive list. They are included because substantial resources have been expended to correct them at existing projects, and consequently, they should be considered in all sedimentation studies. Each project will likely have its own unique problems which will need to be added to this list.

4-7. Bank Caving. Bank caving is a major consideration from two perspectives: in natural rivers there is the loss of adjacent land with the associated introduction of sediment and debris into the stream; and in project reaches there is the possibility of project failure and of removal of land outside the right of way.

a. Erosion Mechanisms. Stream banks are eroded by hydraulic forces imposed by the channel flow, by waves, by local surface runoff cascading down the bank and by geotechnical processes. Erosion from surface runoff is generally a local scour problem and will not be discussed here.

(1) Hydraulic forces. When bank erosion occurs because water flowing in the channel exerts stresses which exceed the critical shear stress for the bank soils, the erosion mechanism is attributed to hydraulic forces. Two cases are proposed:

(a) tangential shear stress caused by drag of the water against the bank, and

(b) direct impingement of the water against the bank.

(2) Erosion from waves. Boat waves can create bank erosion in confined reaches. Wind waves deserve attention in areas having long fetches.

(3) Geotechnical failures. Often, caving banks are due to bank slope instability and not to hydraulic erosion.

(a) A common cause of geotechnical failure is hydrostatic pressure in the soil column. When the hydrostatic pressure in the soil column becomes equal to that of the water-surface in the channel , and the river stage falls more rapidly than the pressure can equalize, a geotechnical failure of the bank will occur.

(b) Another cause of geotechnical failure is rainfall or snow melt water which percolates into the soil column only to reach an impervious clay lens and be diverted to the stream bank. Proper control of bank drainage will correct the problem in these cases.

(c) A third cause results from degradation of the stream bed causing bank heights to increase beyond the stable value for the bank slope.

b. Erosion Rates and Quantities. There is no theory for predicting the rate of bank erosion of a channel.

(1) Rates of bank line movement. That process is normally quantified from aerial photographs. Periodic overflights are traced onto a common base and the bank movement is measured and converted to units of surface acres lost per mile per year. A more precise technique for observing the rate of lateral movement of the bank line is to establish a base line with ranges from it to the bank. However, the aerial mosaics are sufficient.

(2) Volumes of sediment eroded from the bank. Once the surface area is known, bank heights from the field reconnaissance or from channel cross sections, can be used to calculate volumes of sediment eroded.

(3) Weight of sediment eroded from the bank. The specific weight and particle size gradation are both needed from field measurements to calculate sediment yield by grain size class.

c. Destination of Bank Sediment. Whether or not the sediment eroded from the bank is being transported away by the flow can be determined by the appearance of the toe. If a talus is present and covered by tree growth, the bank is not active. Sediment which fell into the stream is being left there. If the bank is steep to the toe, the sediment falling from the bank is being transported away. That bank is active.

d. Field Reconnaissance. As described in the section on river morphology, lateral movement of the channel is one of nature's degrees of freedom. That is, bank caving will occur even though the net channel width remains constant. In all cases, however, make a careful inspection of the site to determine the failure mechanism (Appendix E). Include personnel from hydraulics, geotechnical and environmental disciplines on the field inspection team.

(1) Channel bends. Inspect the point bar for sediment deposition which is pushing the channel flow toward the outside of the bend. Normal channel meandering is expected to move the channel in the downstream direction. A hard point will interrupt that process.

(2) Gravel bar movement. In gravel bed streams, it is common to view a train of gravel bars moving down the channel. The front of each bar is at an angle with the center line of flow, and that angle swings back and forth from one bar to the next. These bars are probably set into motion by the higher flows, but when the flow is relatively low the front of the bar directs current into the bank line. Because the successive bars are angled toward alternate banks, the flow attacks first one bank then the other. The attack moves along the bank as the bars move down the channel.

(3) Increase in channel width. When both banks show erosion with no accompanying degradation with a resulting net increase in channel width, suspect an increase in mean annual water discharge or an upward shift in the flow duration curve. The channel is adjusting to that new flow regime. Such bank erosion is being produced by a completely different mechanism from bar-building, gravel bar movement or bank failure.

(4) Seepage. Inspect the bank line for seepage, for clay lenses, for slope failure lines, and for tension cracks. Tension cracks suggest the bank height is too great for the soil to be stable on the current bank slope.

(5) Dispersive clays. A type of clays exist, known as dispersive clay, which lacks the cohesive attraction common to most clays. Their permissible velocity is considerably below the range normally quoted for clay material. When making the field inspection, suspect such a clay where rills are cut

deeply into a bank of clay material or into mounds of clay which have been excavated from a channel. Therefore, the engineer should beware that the presence of clay banks does not guarantee that bank material can resist high shear stresses or velocities.

(6) Farming or maintenance practices. Farming or maintenence practices which clear off native vegetation right up to top bank will accelerate bank caving unless over-the-bank drainage is controlled. The process is aggravated by, and should be attributed to, the poor farming practices.

(7) Access/egress points. Cattle or vehicle access to the channel weakens the soil structure and removes native vegetation. Bank erosion often results. The problem typically migrates both upstream and downstream from the initial point of disturbance.

4-8. Channel Bed Scour and Deposition. Changes in the bed elevation because of scour and deposition are classified as local scour and deposition or general scour and deposition.

a. Scour.

(1) Degradation. Degradation is the term describing a general lowering of the stream bed elevations due to erosion of the bed sediments.

(a) Reduction in sediment supply.
The significance of the trend is often masked by the slow rate of growth, but a degrading stream is a potentially severe problem which should be investigated to discover the cause and develop a solution. For example, sediment deficient water released to the channel downstream from a dam has the potential to cause generalized scour. When inflowing water is deficient in sediment of the size classes forming the bed, degradation will start at the point of inflow and move in the downstream direction.

(b) Base level lowering. Another common type of degradation is head cutting. Head cutting is a discontinuity, i.e., a rapid drop or waterfall, in the stream bed profile which moves in the upstream direction. It occurs when the channel bed sediment is weakly cohesive and the base level of the stream is lowered. Head cutting is an important consideration because it promotes bank caving; it causes bridge failures as well as failure of other structures in its path; and it increases the sediment discharge into the receiving stream.

(2) Local scour. Local scour is the term applied when erosion of the channel bed is limited, in plan view, to a particular location. It can occur in otherwise stable reaches of a stream as the direct result of a disturbance to the flow field. The maximum depth is difficult to measure since the most severe scour will often occur during the peak flow and deposition will fill in the scour hole as the hydrograph recedes. Local scour should be regarded as a potentially severe problem in any mobile bed stream.

(a) Bridges. Because of their number, bridges are the most frequent location of local scour problems. The process is usually very rapid. Scour

gages consisting of drilled holes in the stream bed back-filled with colored sand, brick chips, or chain have been used to measure scour depths.

(b) Drop structures. Local scour shows up as a deep hole flanked by bank caving. Standard drop structure designs require bed and bank armoring to control this type of scour.

(c) Low weirs. Local scour erodes the bank at the abutments causing the structure to be flanked. Prevent flow from short-circuiting by creating long flow paths. Design for low energy losses at initial overtopping.

(d) Miscellaneous. Local scour also occurs at the downstream junction between riprap or revetment and the natural earth channel. Channel training dikes cause local scour.

b. Deposition.

(1) Aggradation. General deposition, like general scour, spans long reaches of a stream. When the concentration of inflowing sediment exceeds the transport capacity of the stream in that reach, the deposition process starts at the upstream end of the reach and moves toward the downstream end. However, there is a feed back loop. That is, as the deposit moves downstream the backwater effect is reflected in the upstream direction which results in more deposition.

(2) Local deposition. Local deposition compares to aggradation like local scour compares to degradation. It refers to a deposition zone that is limited in aerial extent. It implies nothing about the severity of the problem.

> For example, when the channel width expands, transport capacity will decrease. Sand and gravel will deposit as a center bar because the particles are too heavy to move laterally. During the intermediate range of flow depths, this center bar will deflect water toward both banks. If the banks are unprotected, bank erosion would be expected and that would initiate a new plan-form alignment starting at the center bar and progressing downstream.
>
> On the other hand, streams which are carrying silt and clay would be expected to deposit sediment in the eddies formed on either side of the expansion until a narrower stream width is produced.

c. Field reconnaissance. The following symptoms of general aggradation problems are given to aid in assessing the condition of a stream. When other symptoms are recognized, they should be added (See Appendix E).

(1) Plan-form changes. When the plan-form changes from straight to meandering in the direction of flow, with no actively caving adjacent banks and no bar building, the inflowing sand and gravel loads are in balance with the transport capacity of the stream. However, when there is such a plan-form change in the presence of actively caving banks, the inflowing sand and gravel loads probably exceed the transport capacity of that stream reach causing aggradation. When the plan-form changes from straight or meandering to

braided the inflowing sand and gravel loads very likely exceed the transport capacity of that reach.

(2) Meandering. Active meanders, those at which there is active bank caving, are more likely to be associated with an aggrading reach than a degrading reach. Bank caving in a degrading reach is more likely associated with bank failure than with meandering.

(3) Channel avulsions. When a channel avulsion has occurred and there is no evidence of a downstream, hydraulic control, the inflowing sand and gravel discharge exceeded the transport capacity of the stream in that reach and deposition filled the channel causing the water to seek another place on the valley floor.

(4) Local energy gradient. The significant slope in understanding the micro-behavior, i.e. the reach by reach behavior, of sand and gravel bed streams is the reach energy slope not the general slope of the stream.

4-9. Methods for Calculating Channel Bed Scour and Deposition.

a. General Scour and Deposition. The locations, volumes, and bed-change elevations are calculated by numerical modeling methods, such as HEC-6, in which the sediment transport equations are coupled with the continuity of sediment equation. The application is discussed in Chapter 6.

b. Head-cuts. The sediment routing models like HEC-6 will identify conditions conducive to a head-cut by locating zones of intense erosion. They will transport sediment across a head-cut; but they will not calculate the rate of upstream movement of the head-cut.

c. Scour at Bridges. Local scour cannot be calculated with aggradation/degradation mathematical models such as HEC-6 or TABS-2. However, such models will calculate the base level for the channel bed. Equations to predict the depth of scour at bridge piers, below that base level, may be found in references [49], [2], and [48]. While the equations vary somewhat, the basic variables are width of a bridge pier, shape of a bridge pier, skew angle of the bridge, depth of flow, velocity of flow, and in some cases grain size distribution of the bed material.

4-10. Design Features to Arrest Bank Erosion.

a. Direct Protection. Direct bank protection is applied directly to the bank and includes riprap, gabions, other types of flexible mattresses, and rigid pavement. It is used to prevent further erosion when the erosion mechanism is hydraulic forces. It is used with bank sloping and bed stabilization to provide protection when geotechnical failures are occurring. Such protection usually increases local turbulence and care must be taken that local erosion is controlled at the end of protection.

b. Indirect Protection. Indirect protection is used to alter bank alignment. It includes impervious dikes and pervious dikes and is constructed away from the bank in such a manner to deflect or dissipate the erosive forces

of the stream. Care must be taken to insure that deflected currents do not induce erosion at some other location; consequently, it is much more difficult to design indirect bank protection structures than active protection because the 3-dimensional flow and sediment distribution has to be very carefully defined. Passive protection is subject to increased maintenance due to drift accumulation.

c. Grade Control. When bank failure is occurring due to excessive bank height, and not bank erosion due to point bar deposition, grade control that reduces the bed slope can be effective.

d. Section 32 Program. This program was authorized by the Stream Bank Erosion Control Evaluation and Demonstration Act of 1974 (Section 32, Public Law 93-251) [65]. The legislation authorized a five year program which, among other things, consisted of an evaluation of existing bank protection techniques, construction of demonstration projects, and monitoring the projects to determine the most promising methods. The final report is quite extensive and comprehensive. Copies of the report and its various appendices are available from the National Technical Information Service in Springfield, Virginia.

4-11. <u>Design Features to Control Aggradation.</u> The Corps of Engineers engages in preventing aggradation when it impacts on navigation or flood control projects or when special authorities have been assigned by Congress. The approaches are debris basins, maintenance dredging, and stabilization of channels producing the sediment. Of course, erosion control is a viable alternative if permitted in the authorizing documents.

a. Debris Basins. The design of debris basins is discussed in Chapter 5, Reservoir Sedimentation.

b. Maintenance Dredging. Often the most economical method for handling aggradation problems is periodic dredging. Numerical modeling is the computational framework for estimating the location and amount.

c. Upstream Grade Control. These measures reduce the bed material load when there is excessive degradation.

4-12. <u>Design Features to Control Degradation.</u>

a. Drop Structures. The purpose of drop structures is to reduce the energy slope of the channel so the bed shear stress becomes less than the threshold for erosion of the bed sediments. Design details for the structures are found in reference [55]. In addition, the following details are pertinent for assuring the structures function properly.

(1) Spacing. Spacing between drop structures is critical. Be aware that spacing depends on the inflowing water discharges, the concentration of the inflowing bed material sediment discharge, the gradation of those discharges, and the resistance to erosion of particles on the channel bed. It is not satisfactory to assume historical concentrations and particle sizes when designing drop structures to reduce bank caving because the structures, if

they are successful, will reduce the sediment concentration and may even alter particle size distributions. Therefore, develop the spacing with considerable care. Numerical models such as HEC-6 provide the computational framework for setting spacing.

(2) Local scour. The weak link in most designs are the abutments. The stilling basin below the structure will dissipate the excess energy in the water spilling over the crest, but it does not protect the abutments from local scour when water first starts to spill around the ends of the structure. Efforts to protect against flanking have met with varying degrees of success. The most successful designs are those which pass all flow through the structure.

b. Low Weirs . Low weirs are provided to environmentally enhance channels by providing adequate habitat for aquatic species during low flow periods when the channel would normally be dry. The height of these weirs is normally less than one-third of the tailwater depth at the project design flow line. This height insures little or no head loss with the design flow. However, at low flows the low weir acts like a drop structure and must be designed accordingly [4]. Since water does flow around the ends of these structures, protection must be provided to the stream banks to prevent local erosion.

Section III. Flood Protection Channel Projects

4-13. Sedimentation Problems Associated with Flood Protection Channels. Whereas reservoirs lower flood stages by using storage to reduce the peak runoff discharge, flood protection channels use hydraulic means to reduce flood damages. Design features include levees, flood walls, reduced hydraulic roughness , channelization, cutoffs and diversions. The objectives are to confine the flood stages inside levees or flood walls, to lower the flood stages by diverting part of the flow around the problem area, to lower the flood stage by channelization or to lower the flood stages by reducing hydraulic roughness. A consequence from lowering flood stages is increased flow velocities. All project alternatives affect one or more of the six degrees of freedom of the natural river to some extent. For example, just having a project requires that erosion of the channel banks be prevented.

4-14. Key Locations. Not all locations in a project are equally likely to experience sedimentation problems. Problems are likely to start at the following locations:

a. Braided channels

b. Changes in channel width

C. Bridge or other structures built across the stream

d. Channel bends

e. Abrupt changes in channel bottom slope

f. Long, straight reaches

g. Tributary and local inflow points

h. Diversion points

i. Upstream from reservoirs or grade control structures

j. Downstream from dams

k. The downstream end of tributaries

l. The approach channel to a project reach

m. The exit channel from a project reach

4-15. Maintenance Requirements. Whereas channel improvement refers to improvement in the hydraulic characteristics such as increased conveyance and lowered flow lines, channel deterioration is concerned with deteriorating characteristics such as decreased conveyance or degradation of the bed profile. A man-made earthen channel begins to deteriorate as soon as it is completed. Vegetation begins to grow on the banks, thereby increasing the resistance to flow. In a sand bed channel, bed forms occur which may also increase the resistance to flow. The channel may begin to change its alignment to a less efficient configuration. Bed degradation may occur. These are but a few examples of channel deterioration. Maintenance is required to preserve design capacities. The amount of maintenance depends on how much the design conditions are out of balance with the natural, dynamic equilibrium of the system. In the absence of maintenance, project failure can be anticipated.

a. Maintenance of Organic Debris and Vegetation Control. Organic debris, items such uprooted trees, are carried and deposited by the water. Organic debris control refers to the handling of such items before they become a problem. There have been cases when simply sawing the root ball off the tree would allow both to be washed out of the system with no problems. In other cases, the debris has been removed from the channel and burned. Not only do these activities reduce hydraulic roughness, they eliminate the opportunity for flow to be diverted into a bank by a fallen tree because its root ball got hung up on a nearby bar. In urban areas mowing and live vegetation control are part of the routine, long term maintenance requirements.

b. Maintenance to Remove Deposits from Aggrading Channels. Channel deterioration due to aggradation occurs when more sediment reaches the project than the project channel is capable of transporting. One maintenance requirement is the removal of those deposits to preserve hydraulic conveyance. Otherwise complete blockage of the channel can be expected. This is a long term problem.

(1) Long term maintenance. The volume of dredging is estimated by calculating the average annual sediment yield entering the project reach, calculating the average annual sediment yield the project is capable of

passing and subtracting the two. If the result shows deposition, that value is the average annual dredging that will be required to maintain hydraulic capacity. This approach recognizes that the average annual value will be exceeded by several times if the year is unusually wet. During dry years, no dredging is expected. However, in the long term the dredging quantities will average out.

(2) Design event maintenance. Some maintenance is always expected after a design flood. Bank protection needs repairing. Areas suffering from local scour or deposition need attention. Office records of the average value for streams in the area provide the best information for this maintenance requirement.

c. Maintenance to Prevent Channel Deterioration Due to Degradation. If the comparison between sediment yield entering the reach and that leaving the reach shows erosion, the channel must be maintained to resist degradation.

d. Maintenance to Overbank Areas . If the channel capacity is not preserved, flooding in overbank areas will become more frequent. Sand deposits have become several feet thick over large areas which is quite damaging to agricultural land because very little vegetation will grow on such deposits. If the overbank area is hardwood forest, deposition of a foot or more will kill the trees by suffocation. These problems are usually too great to be resolved by maintenance.

e. Maintenance to Tributaries. If the main channel deteriorates due to aggradation, water surface elevations are raised. This in turn raises the water surface on tributary streams. In steep terrain the effect on land adjacent to the tributary is probably negligible, but in relatively flat terrain the increased water surface elevation at the mouth of the tributary will create backwater effects up the tributary. On the other hand, if the mainstem channel deteriorates due to degradation, then degradation is likely on the tributary.

4-16. Determining the Boundary of the Study Area. The study area for a flood protection project is the extent of the watershed that will be affected by the project, and that is always larger than the project area. The limits of the study area are often difficult to determine because the effect of changes due to the project can extend for a considerable distance upstream and downstream from it. The effects may also extend up tributary streams. Consequently, a large area can be affected by changes along one reach of a stream. In some instances, the boundary may be well defined by control points such as dams or geologic controls. In most instances, the study boundary will not be well defined and the engineer must make a judgement decision. In these cases, the final boundary must be selected after consideration is given to the historical behavior of the river, current behavior, the relative size of the project and the type, amount and location of available data. Points of caution when defining the study area are as follows:

a. Availability of data. If there is no data available for areas outside of the project boundary and time or cost constraints prevent

additional data collection, this area cannot, of course, be included in the analysis. That does not relieve the engineer from the responsibility of making a sediment investigation from which the appropriate recommendations for the project can be concluded. Recommendations for data collection should be a part of such a study.

b. Sensitivity of adjacent reaches. The decision to include or not to include these reaches will likely depend on how much the proposed project features deviate from the characteristics of the natural river.

c. Sensitivity of system to changes in project reach. If the project reach is on a small tributary to a larger stream, it may have no effect on the larger stream even though the project causes drastic changes to the tributary. For example, if a tributary contributes 2 per cent to the total sediment discharge of its receiving stream, it would be unlikely that a project that doubled this contribution to 4 per cent would have any significant effect on the receiving stream.

d. Approach and exit channels. Design features for the approach and exit channels to the project reach can return river hydraulics to preproject conditions thereby reducing the size of the study area.

4-17. Design Features to Reduce Flooding. These features are listed in order of there preference from the standpoint of minimizing sedimentation problems. "More or fewer problems" is a relative comparison to what existed in the natural stream before the project was constructed. The philosophy is to leave the natural channel untouched to the maximum extent possible because the natural river is the best model of itself.

a. Levees and Flood Walls. These are desirable design features because they can be constructed without disturbing the natural channel vegetation, cross section or bottom slope. Usually, there is no immediate effect on sedimentation from implementing this type of modification. However, there may be a long-term channel aggradation problem. Numerical sediment modeling is the computational framework for design calculations.

(1) Influence on hydrology. The flood hydrographs will likely peak at higher water discharges because the project has eliminated storage. On the other hand, additional storage is often mobilized under the backwater curve which extends upstream from the project reach. That will tend to offset the impact of the project. A hydrology study is required to determine which controls. The design flow for a project differs greatly from the day to day flows that have shaped the channel . Therefore, the impact of the full range of flow conditions should be evaluated in a sediment study.

(2) Sedimentation problems in the project reach. Always address bank erosion, aggradation and degradation even though changes from historical conditions are expected to be minimum.

(a) The historical rates of bank caving will probably continue with the project in place. Therefore, the need for bank protection must be carefully analyzed.

(b) The percentage of total flow carried in the channel may increase to the point of causing erosion of the channel bed. Shield's parameter is one method for checking stability. A better method is to use a numerical model such as HEC-6.

(3) Influence on the stream system. The water surface profile at the upstream end of the leveed reach is likely to be higher than it was under natural conditions. That will allow sediment to deposit under that water surface profile upstream from the project. At the downstream end of the exit channel the tailwater rating curve will not change from the preproject relationship. That could trigger a deposition zone if scour is permitted in the project reach.

(4) Long term maintenance. If the project is in an aggrading reach of the natural river, continued aggradation should be anticipated in the future. That can be calculated with a numerical model. Another maintenance item is care of the vegetation which will continue to grow. Not only will it cause aggradation by trapping sediment but it will also increase hydraulic roughness.

b. Reduced Hydraulic Roughness. Mowing in urban areas, or clearing and snagging in rural areas, are popular types of channel modification. In the context of this paragraph, vegetative clearing includes clearing and snagging of debris from the channel bed or selective clearing of growing vegetation. Except for those about to fall into the channel, avoid stripping trees from along the top bank line.

(1) Influence on hydrology. The influence on hydrology is subtle but significant. It results from lowering the water surface elevations. When that occurs, flood plain storage decreases. Flood hydrographs leaving the improved reach may have higher peaks than previously.

(2) Potential sedimentation problems in the project reach. The water velocity will increase because of the reduced hydraulic roughness, and channel erosion is a potential problem. If deposition was occurring before the project, it may or may not continue. Numerical modeling is the computational framework to forecast the project condition.

(3) Influence on the stream system. The upstream end of the project reach has a potential for a head-cut because the stage-discharge curve is lower than it was under natural conditions. Tributary streams also have the potential for head-cuts because of the lower base-level in the receiving stream.

(4) Long term maintenance. Sediment deposition and erosion may be different from historical rates because of better transport through the project.

c. Channelization-Natural Boundaries. This channelization refers to lowering the flood stage of the stream by widening, deepening, smoothing, straightening or streamlining the existing channel. One should plan for a detailed sediment study.

(1) Influence on hydrology. The effect is the same as described for levees and flood walls except carried to a greater extent. That is, storage will be eliminated through the project reach and the project will not create a backwater curve in the upstream direction to help regain that loss.

(2) Potential sedimentation problems in the project reach. A channelized project may perform well or the system may fall apart depending on the design. However, it is much more likely to experience sediment problems than either the levee approach or the reduced hydraulic roughness approach. The type of problems and their severity depends upon how stable the natural channel was in the project reach and how much the design channel dimensions depart from regime values.

(a) Width. In general, fewer sediment problems are expected when the design cross section is constructed by cutting one bank or the other but not both banks, figure 4-1. The most common problems arise when the design bottom width is not in regime with the natural system. Perennial streams typically have a low flow channel. If a wide, flat-bottom channel is constructed, a low- flow channel will often develop within it and the meander pattern will allow that low flow channel to attack first one bank of the project channel then the other. Therefore, channel designs for perennial streams should follow the cross section shape of the natural where possible. Ephemeral streams in Southwest United States, on the other hand, often exhibit a wide, flat sand bed and no low flow channel. Designs for those streams should follow that cross section shape.

(b) Depth. A second problem is a design channel that is too deep or too shallow. Depth refers to channel bank height. It is necessary to observe geotechnical factors, but that is not sufficient to achieve good sediment transport characteristics. The depth providing the best performance is that along a stable, alluvial reach of the natural stream. That is often associated with an annual peak discharge approximating the 2-year flood; however, always inspect the streams local to the project to aid in selecting a suitable depth. This approach to the elevation of the compound cross section shape should be balanced with environmental considerations for grass cover on the floodway berm, figure 4-1.

(c) Alignment. A third consideration in design is the alignment of the channel. The best choice is to follow the alignment of the natural channel. If the alignment is changed, it may require protecting the bends; furthermore, if the channel is straightened, bank protection requirements may be increased to include both banks .

(d) Another common problem is a change, between the natural channel and the design bed elevation of the project channel, in the gradation of sediment on the channel bottom. This becomes a problem when the design cuts through a clay lens into a less resistant material which can be eroded by the flow, figure 4-2.

(e) Hydraulics. Channelization collects more of the total runoff into the channel portion of the cross section. Consequently, the flow distribution across the cross section will be different with the project than it was before. Possible erosion of the channel bed should be investigated.

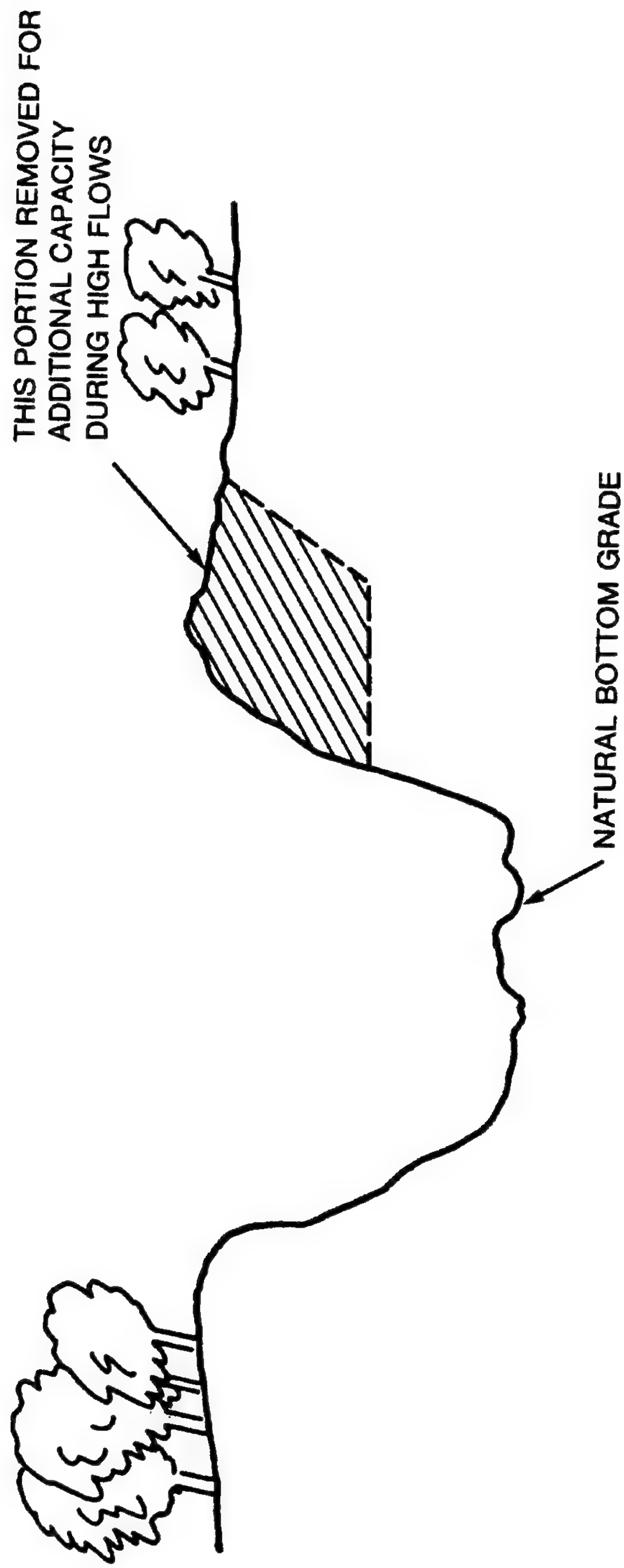


Figure 4-1. Compound cross section shape

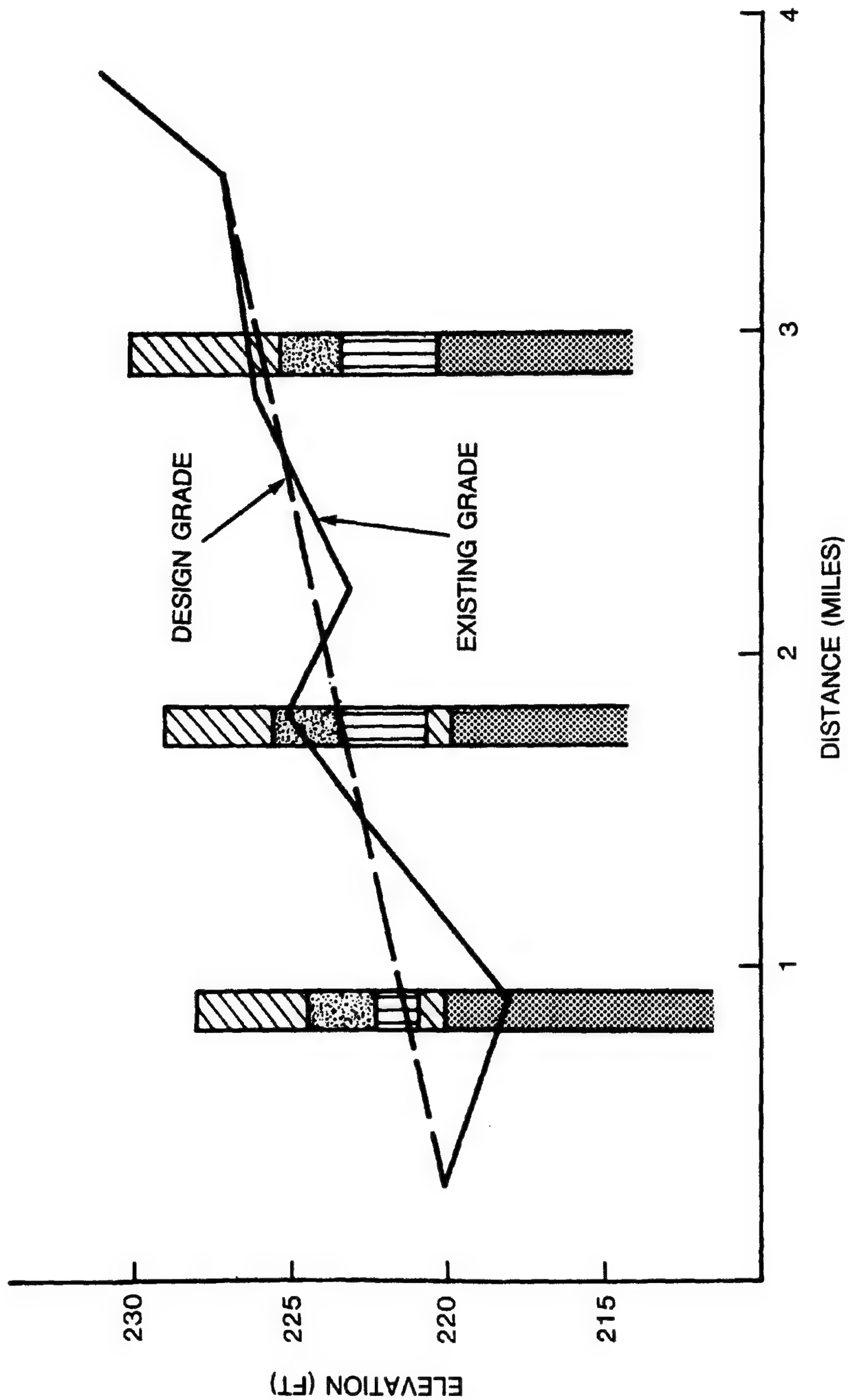


Figure 4-2. Use of boring logs in selecting design grade

(3) Influence on the stream system. Channelization has a more extreme impact on the stream system than reducing the hydraulic roughness does. It is of the same type of impact, however, and that is lowering the base level of the system. Sedimentation problems need special attention in the approach and exit reaches, figure 4-3.

d. Channelization-Rigid Boundaries. This design feature is used to minimize land requirements and protect against the high velocities associated with steep slopes. Measures are similar to those used in natural boundary channelization. The design goal is to maximize channel capacity and minimize flood stages. Erosion is not a problem, but sediments can eventually roughen the channel lining. There is a potential for deposition problems and that needs careful evaluation. Debris basins are common with this design approach.

e. Cutoffs. Channel cutoffs provide immediate and significant reductions in flow lines through and above the cutoff area. To avoid steepening the channel slope, at the low to mid range of flows, high level cutoffs are proposed, figure 4-4. Analysis of the extent of the potential scour and deposition is necessary to insure that the cutoff will function as designed after a new equilibrium condition is established. Numerical modeling is the computational framework for analyzing sedimentation in flood channel cutoffs.

(1) Potential sedimentation problems in the project reach. When all of the flow passes through the cutoff, the usual problem is degradation as the result of a steeper slope. However, when only part of the flow passes through the cutoff, deposition can be expected either in the old bend way or in the cutoff. Erosion of the outside of the bend is probable and a revetment should be considered.

(2) Influence on the stream system. Cutoffs contribute to scour of the channel bed above the cutoff and channel deposition below the cutoff. This process will continue until an equilibrium condition is attained. This equilibrium condition may be unacceptable hydraulically because deposition downstream of the cutoff can significantly raise flow lines. However, the stream will attempt to regain its length, armor its bed, adjust bed roughness, and/or deposit the bed material load with associated bank erosion.

(3) Long term maintenance. Some flood channel cutoffs are high level in that only the flood flows spill into them. To be effective, vegetation and debris maintenance is required. Land use in the cutoff must be restricted.

f. Diversions. The location of the diversion, relative to the bend, point-bar, crossing sequence indicates whether the sediment outflow will be less than or greater than the concentration left behind. Physical models are the most reliable approach for designing diversions.

(1) Potential sedimentation problems in the project reach. As with cutoffs which take only part of the total discharge, deposition is a common problem at diversions. Both local and general deposition are likely. Numerical sediment modeling is the computational framework for predicting

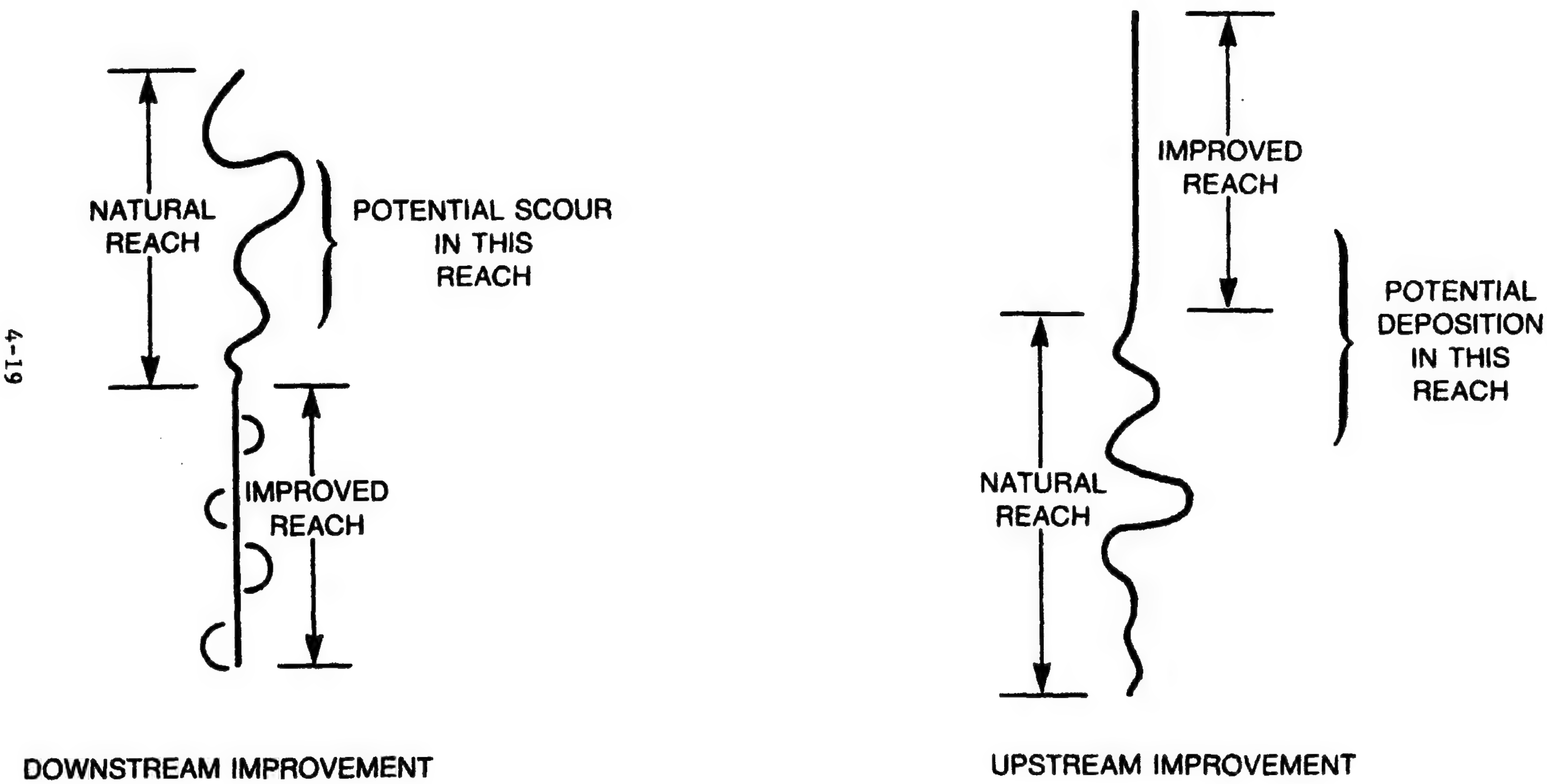


Figure 4-3. Effects of abrupt channel improvement

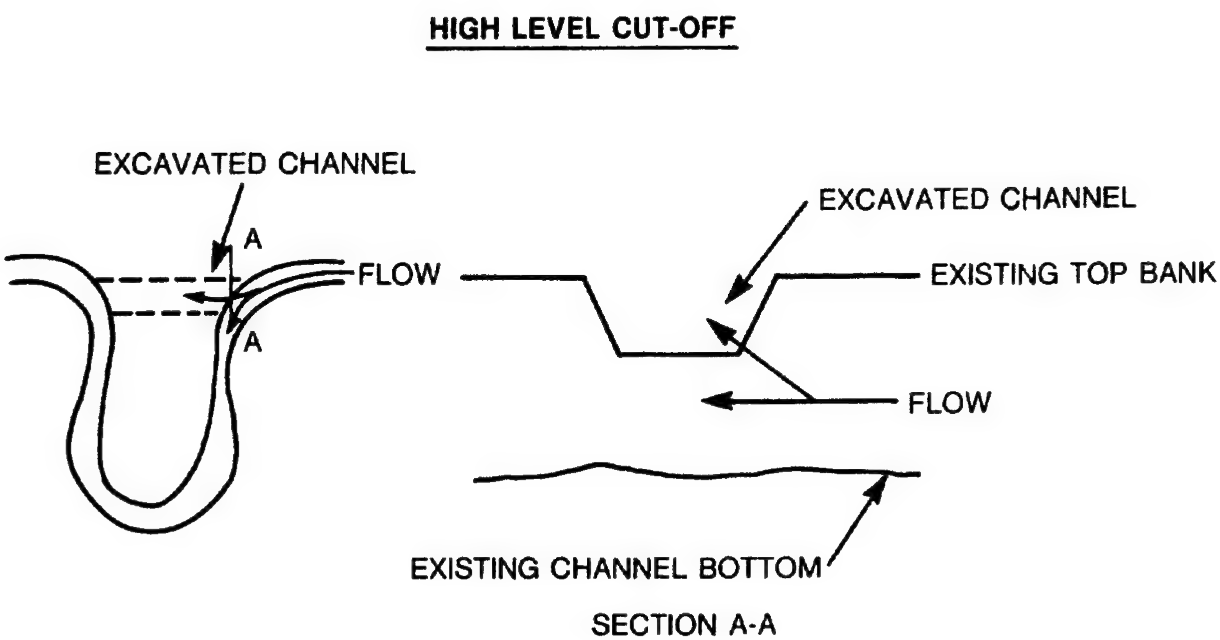


Figure 4-4. Illustration of high level cut-off

quantities and locations of deposits provided the concentration entering the diversion channel is known. Physical modeling is the most reliable approach for predicting the concentration of bed material load entering the diversion channel.

(2) Long term maintenance. The volume of sediment to be removed can be estimated using the sediment budget approach, and numerical modeling will indicate locations of the deposits. Recent cases in which land in the diversion floodway was converted to other uses makes this an unattractive feature because it could not be maintained.

g. Pump Plants. These structures are susceptible to deposition in the inlet channel at the head of the land side pool. Also, once the receiving stream has dropped, the outlet channel of the plant is susceptible to scour since much of the sediment has settled in the relatively slow moving pool water. In these respects, pump plants act like small reservoirs. The engineer should be aware that such drawbacks exist under design conditions.

h. Reservoirs. Although reservoirs are not constructed as frequently now as they were in the past, this is still an important type of channel

modification. Reservoir sedimentation is discussed in Chapter 5.

i. Debris Basins. Debris basins are used to reduce the inflowing sediment discharge for those particle sizes which will deposit in the channel project. Design considerations are discussed in Chapter 5, Reservoir Sedimentation.

Section IV. Navigation Channel Projects

4-18. Sedimentation Problems Associated with Navigation Channels. The objective in navigation channel design is to provide a channel of specified depth and width along an alignment that does not shift from side to side across the channel. Although the water-sediment behavior is similar to that in flood protection channels, the question being addressed is different. A flood project seeks to reduce the stage. A navigation project seeks to provide reliable water depth. The two are sometimes complementary and sometimes competitive requirements. The yield of sand is significant to both. Silt and clay are common materials dredged from navigation channels, whereas silts and clays are not common problems in flood channel studies, except in backwater and salinity areas. Another significant difference between the two channel uses is the resolution required to locate problem areas. Even one shallow crossing will obstruct navigation whereas that probably would not significantly change the stage of a flood. Finally, low current velocities are attractive in a navigation project and that often conflicts with sediment transport requirements.

4-19. Key Locations. Not all locations in a project are equally likely to experience sedimentation problems. Focus on the following locations:

a. Bridge or other structures built across the stream

b. Long, straight reaches

c. Crossings

d. Short radius bends

e. Increases in channel width

f. Tributary inflow points

g. Diversion points

h. Upstream from lakes or streams controlling the backwater curve

i. The downstream end of tributaries

j. The approach channel to a project reach

k. The exit channel from a project reach

4-20. Maintenance Requirements.

a. Long Term Maintenance. The volume of dredging is estimated by calculating the average annual sediment yield entering the project reach, calculating the average annual sediment yield the project is capable of passing and subtracting the two. If the result shows deposition, that value is the average annual dredging that will be required to maintain hydraulic capacity. This approach recognizes that the average annual value will be exceeded by several times if the year is unusually wet. During dry years, no dredging may be needed. However, in the long term the dredging quantities will average out.

b. Design Event Maintenance. Some maintenance is always expected after a large flood. Bank protection and training works need repairing. Areas suffering from local scour or deposition need attention. However, another event to include in sedimentation studies for navigation channel design is the low flow following a flood. A simulation through using the entire flood hydrograph is recommended for leading up to the low flow analysis.

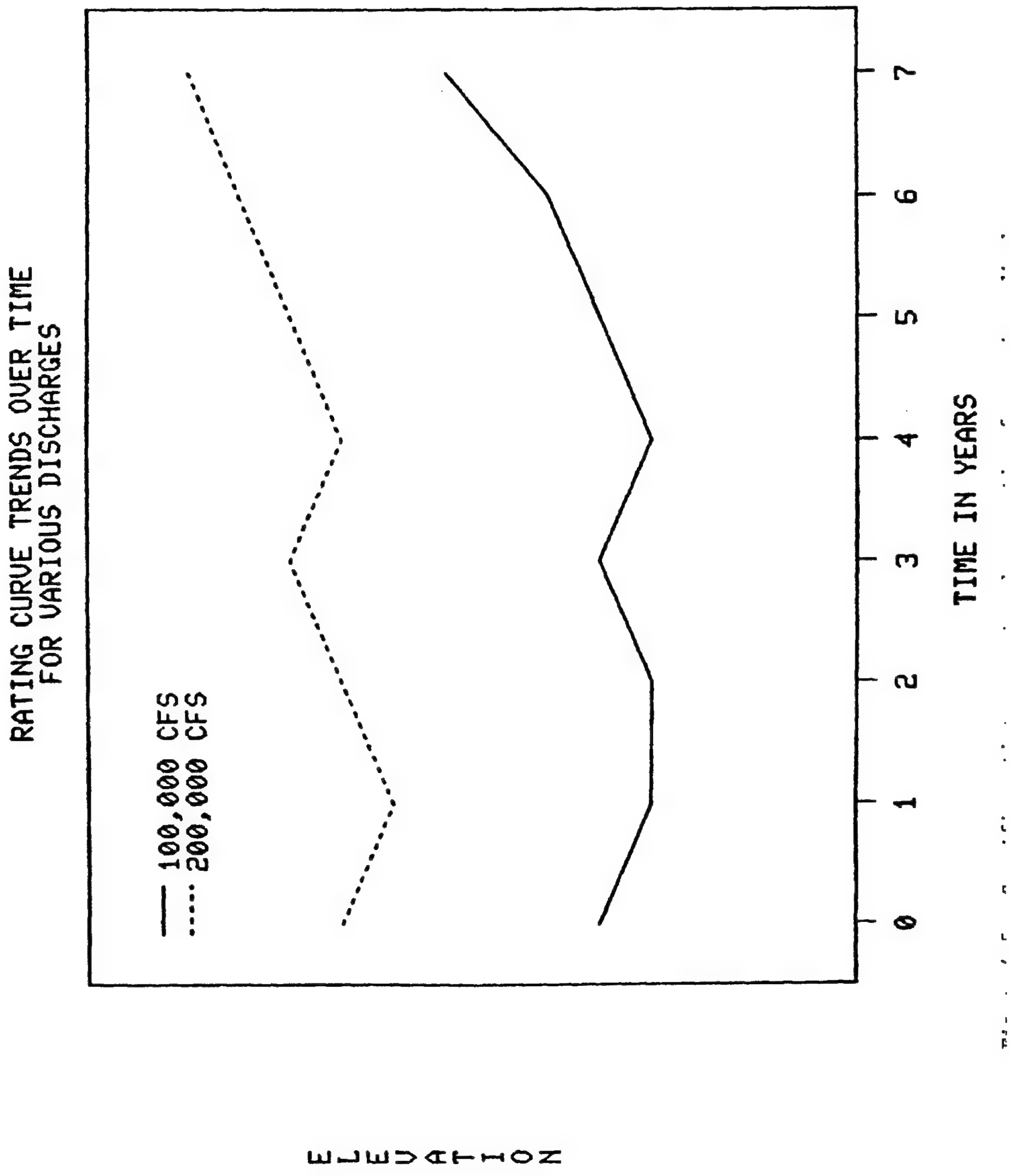
c. Tributary Channel Deterioration Due to Navigation Channel Dredging. When maintenance dredging is so intensive that a lower base-level is perpetuated, bank failure along tributary streams can be expected. A grade control structure at the mouth of the effected tributaries will alleviate the problem by raising the base-level back to the preproject stage-discharge rating curve. Specific gage height graphs will show the extent of base-level lowering, if any, figure 4-5.

4-21. Determining the Boundary of the Study Area. The study area is the extent of the watershed that will be affected by the project, and that is always larger than the project area in the sediment impact assessment study. However, it is possible to decrease the limits of the study area in the detailed studies by collecting sediment data crossing the project boundaries. In some instances, the boundary may be well defined by control points such as dams or geologic controls. In most instances, the study boundary will not be well defined and the engineer must support a judgement decision. In these cases, the final boundary must be selected after consideration is given to the historical behavior of the river, current behavior of the project reach, and the relative size of the project.

a. Data Requirements. The absence of data does not relieve the engineer from the responsibility of making a sediment investigation from which the appropriate recommendations for the project can be concluded. Recommendations for data collection should be a part of such a study.

b. Sensitivity of Adjacent Channel. Reaches adjacent to the project area may not be sensitive areas. The decision to include or not to include these reaches will likely depend on how much the proposed project changes the hydraulic characteristics of the natural river.

c. Approach and Exit Channels. Design features for the approach and exit channels to the project reach can return river hydraulics to preproject conditions thereby reducing the size of the study area.


RATING CURVE TRENDS OVER TIME
FOR VARIOUS DISCHARGES
100,000 CFS
200,000 CFS
ELEVATION
TIME IN YEARS
0
1
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7

4-22. Methods of Analysis. Navigation channel design is more demanding than flood channel projects because the width, depth, location and alignment of the navigation channel are critical. One-dimensional numerical modeling is useful for establishing a "channel trace width" that can achieve a prescribed, long term target quantity of maintenance dredging. Two-dimensional, numerical modeling is useful for designing training works to control expansions and eddys. However, the three-dimensional behavior of flow in sinuous channels requires physical modeling to adequately predict the long term channel characteristics.

4-23. Design Features for Navigation Channels. The following design features start with a stable river channel plan-form and progress to channel modification by cutoffs and chute closures. The structural components used to guide flow in such a way as to maintain an effective main channel along the desired alignment are called training structures. Dikes constructed of either rock or timber piles are most often used. Design details are presented in the engineering manual for layout and design of shallow draft waterways.

a. Navigation Channel Alignment in Stable Reaches. The simpliest problem is one of providing a navigation channel alignment in a stable reach. The proper alignment of the navigation channel will recognize that the bed configuration of an alluvial stream is a series of bends and crossings. It will seek to use that knowledge to minimize maintenance dredging. That is, the bends will have point bars, but both the location and height of the point bars will be fairly consistent from one flood to the next.

> Consistent is not the same as static. Point bars are one of natures locations for storing the bed material load as it moves along the channel. There is a continual exchange of material every flood event. Consequently, bed material which is removed will be quickly resupplied by the next flood event because the bar has to build to its natural height before the exchange process will take place.

Therefore, to minimize maintenance dredging avoid navigation alignments which cross the point bar.

b. Stabilizing or Modifying the Channel Plan-form. A straight channel is not a good plan-form for navigation because the deepest channel shifts around from flood to flood. Training structures can be used to form a meandering pattern within the main channel. However, channel plan-form is one degree of freedom of a river. Therefore, the meander pattern is not an arbitrary sequence of bends and crossings. The river is the best model of itself for establishing the meander wave length and the crossing length. When it is necessary to depart from those dimensions, a considerable effort will be required to establish a successful design.

c. Cutoffs. Cutoffs are constructed to provide a longer bend radius for better navigation conditions. The theory to relate radius of the cutoff to channel width is just developing. Presently, numerical modeling in 1 or 2 dimensions is not adequate to design the cutoff section. The prototype river offers a good model of itself provided one selects bends which are similar to

the potential cutoff. Physical models provide the most reliable insight for cutoff design. However, system analysis using a one-dimensional model such as HEC-6 is advisable if the channel length is reduced significantly.

d. Chute Closure. Flow around a center bar or island loses transport capacity and shoaling occurs. The channel is often unstable and requires considerable dredging. Chute closure is undertaken to reduce dredging by confining enough flow to one main channel. The design encourages deposition by slowing the velocities through the chute. This process will be accelerated when vegetation establishes itself on the deposited material.

e. Dredging. Often dredging is the most economical method for providing the required navigation depth, but that should be decided after an analysis of the other design features. For example, channel size and alignment should minimize dredging in bends. Crossings are the usual depth control, and a dredging option would simply keep the crossings open.

(1) Sorting by particle size. Sediment yield studies for navigation dredging should always provide the total volume of material by size fractions.

(2) Influence of dredging on the stream system. Dredging which returns the sediment material to the channel does not create stream system instabilities like dredging which removes sediment from the system. As long as there is a resupply, there will be no lowering of the base level at tributaries. On the other hand, when the stage discharge rating curves show a degradation trend over time, so much sediment is being removed from the system that base level lowering may cause general degradation up the tributaries. That is a system instability which needs attention.

Section V. Channel Mining

4-24. Channel Mining. The use of stream beds as a source of gravel has increased in recent years. Whichever method is used, gravel mining reduces one of the natural "loading parameters" in the system which can induce significant changes. Bridges have failed after such pits were opened in their vicinity. Therefore, the engineer should be forewarned that such operations should be throughly evaluated prior to their initiation.

4-25. Allowable Quantities and Rates of Removal. There have been no general guidelines established to govern removal quantities and rates. If the stream does not have an excess of inflowing bed material, i.e. if it is not aggrading, then the removal rate and quantity should be no more than the average annual yield of the size classes being removed. When excess material is available in the stream, the removal rate could conceivably be increased, thereby alleviating deposition downstream from the pit. Numerical modeling is the computational framework for establishing quantities.

4-26. Impact of Mining on the Stream System.

a. Upstream. The most common effect upstream from a pit is general degradation with resultant bank failure and channel widening. Such degradation also causes base level lowering on the main stem which can induce general

degradation up tributary streams. Prior to approving the pit the depth of channel degradation should be calculated for a distance sufficiently far upstream to ascertain if bridges, and other structures, are adequately founded. Figure 4-6 [37] illustrates a case history in which the San Juan Creek in Orange County, California was adversely affected by a gravel mining operation. In this case the head cutting upstream from the pit eroded the channel bottom to a depth of 30 feet. The overly tall banks failed and the channel became wider.

b. Downstream. Scour has also been observed downstream from some channel mining operations. In theory, this is because the pit traps so much of the inflowing bed material sediment load that the water flowing out of the pit is much like a sediment deficient release from a dam. This sediment starved water removes bed material from the channel. The bed will eventually become armored if sufficient coarse material is present.

Section VI. Staged Sedimentation Studies

4.27. Staged Sedimentation Studies. Once the study needs have been identified, the engineer must then select an appropriate evaluation procedure. The steps outlined in this section are of general nature; they are offered as a guideline. They are not all inclusive and are given as the least that should be done. The engineer is responsible for supplementing these steps as needed to insure project performance.

4-28. Available Study Approaches. Sediment studies are much like hydraulic studies in that each project has specific requirements. However, sediment studies do share many similarities from project to project. Therefore, while individual studies may vary considerably, the basic approaches are similar. The type of approach depends on several variables as follows:

a. Purpose of the study - question that need answering

b. Physical setting

c. Confidence required in result

d. Data available for the study

The purpose may simply be to determine if a sediment problem does or does not exist in a given reach of stream. On the other hand, the project might be quite complex and the purpose of the sediment study be to calculate as accurately as possible the expected changes in the stream bed and/or sediment discharge during the life of the project. These two extreme purposes require quite different study approaches.

4-29. Sediment Impact Assessment.

a. General. This study approach is recommended as the first step in all sediment investigations. It attempts to discover what sediment problems will significantly affect project performance and/or project maintenance; which "threshold values" might the project cross over that would cause it to fail;

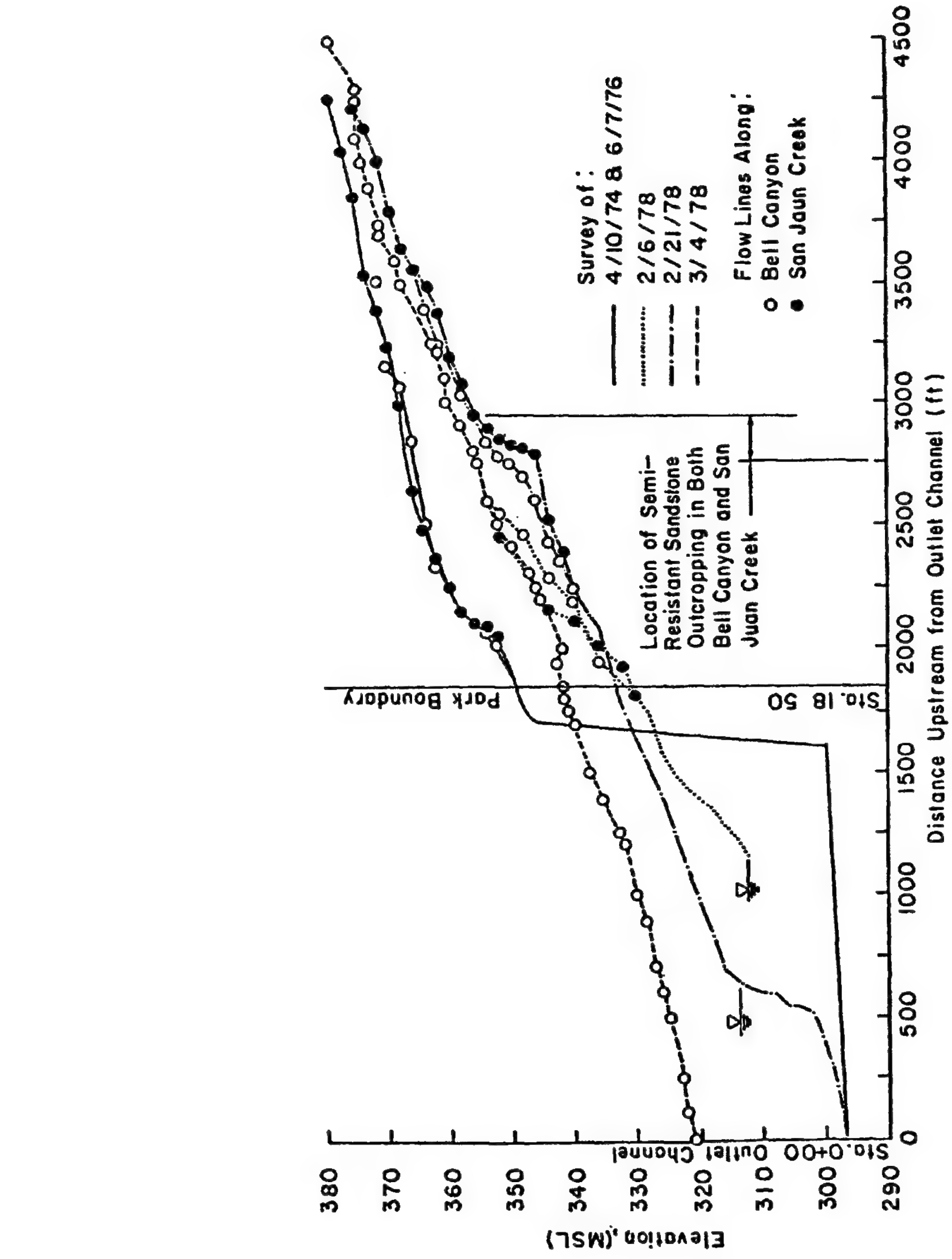

Figure 4-6. Measured bed profiles

which design features of a proposed project may have detrimental effects on this stream; and how severe might those effects be. The sediment impact assessment might suffice for all the sediment investigations required if:

(1) The present reach is stable.

(2) The proposed improvements are minor in nature and do not significantly alter the existing sediment, hydraulic or hydrologic variables.

b. Sequence of Steps.

(1) River geomorphology. Assemble data from all sources. A starting place is the list of sources in Chapter 2 of this manual. Carefully assess the historical stability of the stream system within the project reach, and look both at approach and exit reaches to the project reach. The period of time of interest is the most recent 20-30 years. Refer to Appendix D in this manual for suggested procedures.

(2) Field reconnaissance. Appendix E in this manual has more detailed information on how to conduct a field reconnaissance. The study reach should be inspected to determine if it is stable under current conditions. If it is not, a more complete investigation will be needed, and the Sediment Impact Assessment should recommend what level of detail is appropriate.

(3) Hydraulic parameters for existing conditions. Ideally, these should be obtained from field measurements taken at a standard discharge range. The water velocities, discharges, and water surface elevations are needed to confirm the hydraulic calculations. If that source is not available, use the measurements made on the field reconnaissance to support the hydraulic calculations. In either case the following graphs for the project reach are suggested: a stage-discharge relationship, a depth-velocity relationship, a depth-slope relationship, a depth-bed shear stress relationship, and a depth-percent of total flow in the channel relationship.

(a) Bed roughness. Use a "bed roughness predictor" to tie the hydraulics to the bed sediment samples taken during the field reconnaissance trip. Composite this n value with other roughnesses in the cross section. Plot a graph of channel velocity vs hydraulic radius for the range of water discharges through the project design flood discharge.

(b) Flow distribution between channel and overbanks. Plot the channel velocity from a backwater program for the full range of water discharges. Such a plot should show those velocities increasing with depth. If they decrease with increasing depth, either justify that trend or correct the n-values between the main channel and overbanks before proceeding. Use the channel velocity from the bed roughness predictor as an aid in calibrating the distribution between channel and overbanks in the water surface profile model.

(c) Sensitivity to geometry. If channel characteristics are so varied that one curve is not representative of the project reach, use a water surface profile computer program to calculate the hydraulic parameters. Make two runs: one with the best estimate of n-values from office files; and one using

the predicted bed-roughness n-values for the channel bed portion of the cross section.

(4) Sediment transport for the existing conditions. If measured data are available, separate the total sediment discharge into bed material load and wash load components. Otherwise, select a couple of sediment transport formulas and calculate a sediment transport relationship for the full range of water discharges on the stage-discharge relationship. That will provide bed material discharge curves for existing conditions. If the curves are drastically different, apply a third transport function and select the most consistent one.

(5) Plotting of soil borings. It is very useful to plot the channel boring logs on a channel profile. This allows quick identification of potential problem areas. It will also allow design channel grades to be set in such a manner that the channel will be embedded in erosion resistant material rather than cut into soils which are easily eroded.

(6) Develop design features for the proposed project. Friedkin, in his 1945 study, concluded that,

> "... in erodible materials a river will shape its cross sections in accordance with its flow, slope, bank materials, and alignment, irrespective of its initial cross sections, provided the initial cross sections are not so wide and shallow that the flow does not have sufficient velocities to move sand along the bed and erode the banks. Of practical importance, these tests show that in erodible sediments there is no advantage in digging a new channel for a river deeper than is normally found under similar conditions." [20]

The engineer should realize, on the basis of that quotation, that if the proposed, design cross section is not similar to the regime cross section, sediment problems usually require extensive maintenance to keep the project in operation. This concept is valid for both flood control and navigation channels.

(7) Hydraulic parameters for project conditions. Flow line computations are the only source of this information. If the channel is prismatic and flow is friction controlled, simple normal depth calculations will be adequate. Otherwise, use a water surface profile program. Calculate and plot the same variables as presented above for the existing channel. Use the same stage discharge predictor as for the natural channel, but use the bed material gradations at the invert of the proposed channel as well as those from the natural channel and perform a sensitivity study.

(8) Preliminary screening for sedimentation problems. The velocities in the improved channel should not exceed the maximum allowable velocity for the type of material in which the stream is embedded, reference [55]. If they do, either redesign the channel cross section, include a channel lining, or add design features such as drop structures to flatten the slope. Improved velocities for low flows should not be so low that deposition will be induced beyond that which occurs under existing conditions.

(9) Sediment transport for project conditions. Using the same sediment transport formula, calculate a sediment discharge for the full range of water discharges on the stage-discharge relationship. Plot the calculated sediment discharges on the graph with existing conditions.

(10) Impact of sedimentation on performance of proposed project.

(a) General aggradation or degradation. A sediment budget analysis is proposed to test for general aggradation. The budget is calculated by subtracting the sediment yield of the bed material sediment load for project conditions from that for the existing channel. If the result is positive, aggradation is indicated. If the result is negative, check the bed sediment for resistance to erosion. The sediment yield is needed for both existing and project conditions.

(b) Calculate sediment yield for existing conditions. Using some of the methods presented in chapter 3, calculate the average annual sediment yield for the existing channel. Separate that total into the bed material load component and the wash load component. Devise a flow-duration curve for the project site, and integrate that with the calculated sediment transport curve for the existing channel. The result is average annual yield of bed material sediment. Confirm that result with yields determined by the other methods and reconcile differences before proceeding.

(c) Calculate sediment yield for project conditions. Use the flow-duration sediment discharge rating curve method of Chapter 3 and make a sediment yield calculation for project conditions.

(d) Calculate the sediment budget. The sediment budget is calculated by subtracting the sediment yield for project conditions from the sediment yield for existing conditions. If that result is positive, deposition is indicated. Using simple geometries and available specific weights, calculate how much time will pass before deposition is sufficiently deep to affect project performance. If the sediment budget produces a negative difference, erosion is indicated. Choose design features accordingly.

(e) Design flow analysis. Repeat the sediment budget calculation for the design flow hydrograph, also.

(f) Local scour. At this level of study the approach for estimating local scour potential at bridges and hydraulic structures is to compare this project with similar projects.

(g) Bank erosion. Likewise, the approach for evaluating bank erosion and the need for a protective cover is to compare this project with similar projects.

(11) Estimate long term maintenance. This refers to both local and general scour and deposition in the project reach. The approach for estimating maintenance to arrest local scour at bridges, hydraulic structures and bank protection sites, is to compare this project with similar, existing projects. The approach for estimating maintenance for general deposition is

to use the sediment budget analysis.

(12) A numerical sediment model, such as HEC-6 will make all those calculations and display the results in a table using as much or as little data as is available. It is not expensive to analyze a few tracer discharges when an HEC-2 water surface profile data set exists.

(13) End product. Conclude whether the improvements will or will not cause the reach to be unstable. The type and probable locations of design features should be estimated. If the magnitude of sedimentation problems is important to basic formulation decisions, further study should be recommended. However, if the results of this impact assessment can be changed by a factor of 2 without changing the basic go/no-go decisions about the project, it will probably be acceptable to proceed with formulation, initiate a data collection program, and refine the sedimentation investigation in a detailed sedimentation study.

c. Points of Interest if Performing a Sediment Impact Assessment.

(1) Normal depth approach. Hydraulic characteristics can always be determined from flow line computations, but that is not always necessary.

(2) Complex geometry. The study area may be so irregular that the assessment must be adapted to reaches rather than having one for the entire project. Do whatever is necessary to arrive at defendable results.

(3) Sediment transport. Suitable sediment transport equations are listed in reference [2].

(4) Sediment data. Appropriate data necessary for the chosen equations should have been gathered during the field reconnaissance. Ideally, bed samples should be taken at several different times to insure that a representative bed sample has been obtained. One set is better than none.

(5) Study sequence. The first potential area to study is the upstream end of the project reach. When multiple reaches have been used, potential areas of scour and deposition are identified by comparing the transport capacity of a reach to the transport capacity of the next upstream reach.

4-30. Detailed Sedimentation Study. The Detailed Sedimentation study identifies the location and type of project features that will be required to achieve the project purpose with the minimum amount of maintenance. The primary criteria are "What is required for the project to function without major sedimentation problems, and How will those features affect the stream system?" The sediment routing is done by particle size using a numerical sediment model. Several proven models are available and have been used extensively. An example is the HEC-6 generalized computer program, "Scour and Deposition in Rivers and Reservoirs." The differences between this application and that presented in the Sediment Impact Assessment are in the breadth and depth of the computations and the amount of data that is available. In addition, flow hydrographs should be used instead of just a few tracer discharges, and the period of simulation should span from a single

event to the life of the project. Sensitivity runs should be made to test the response of the project to uncertainties in sediment yield, water runoff or downstream controls. For these reasons, the study results will provide a better basis for developing conclusions than other computation techniques can provide. The following steps are suggested:

a. Field Reconnaissance. Another field investigation is recommended to visually verify data collected since the previous one.

b. Data Collection. Data necessary for the computer program should have been identified and the data collection effort initiated following the Sediment Impact Assessment recommendations. See the HEC-6 user's manual for specific data requirements.

c. Selection of Transport Equation. The measured sediment data previously collected should be used to select an equation that most closely reproduces the measured data over a wide range of flows. When sufficient data were available, the empirical coefficients in one of the standard transport equations have been calibrated particularly for that study.

d. Preparing Data for the Numerical Model. The data must be organized and coded for input into the computer. One of the largest surprises in sedimentation studies is the amount of time required to code and manage the large hydrologic data sets which are required for long term simulation of a network of streams.

e. Confirmation. Any quantitative analysis should be based on predictive methods which have been confirmed. The confirmation process consists of taking past physical conditions and adjusting the calibration variables until the model will reproduce actual measured changes.

f. Prediction. Upon completion of the confirmation steps, a prediction of bed aggradation and/or degradation can be made with a reasonable degree of certainty.

g. Conclusions. The computer output indicates changes in the channel bottom elevation, thereby highlighting potential problem areas. While the program prints out specific numbers, the engineer must realize that the numbers can only be used for comparison with each other and represent only the "average" future behavior for the project reach. Mathematical models are quite capable of predicting bed elevation changes.

4-31. Feature Design Sedimentation Study. This type of study is an extension of the Detailed Sedimentation Study to test the final design of the project and relocation features. It is usually conducted at a specific location on a stream where extensive data are available. It includes all of the original data plus all data collected since the Detailed Sedimentation Study was completed. Examples are the depth of both local and general scour at bridges; the head loss and potential local scour at weirs and drop structures; the potential deposition in expansions and at inflow points; the performance of debris basins in the design; the stability of the channel invert against erosion; the ability of the approach structure to eliminate head-cuts upstream

from the project, the local erosion at the approach structure and the changes in tailwater as the result of changes in the exit channel. Suggested steps are:

a. Field Reconnaissance. A field investigation is necessary to visually verify conditions and data previously collected.

b. Confirmation. At this level of study all hydraulic and sediment parameters will have been comfirmed against field data. The process consists of taking past physical conditions and adjusting the input variables to reproduce an actual measured change. After the predictive equation has been confirmed, the process can be verified by applying it to other data sets and verifying the results.

c. Prediction. The major task is to forecast future land use, hydrology loading and sediment loading. The confirmed model can predict future conditions with a reasonable degree of certainty.

CHAPTER 5

RESERVOIR SEDIMENTATION

Section I. Introduction

5-1. Purpose. The purposes of this chapter are to present the philosophy for measuring the impact of a project on the stream system morphology, to identify potential sedimentation problems in the reservoir, to associate those problems with project purposes, and to propose approaches for analyzing them.

5-2. Scope. The scope of problems addressed in this chapter is limited to flood control and navigation. Related reservoir uses are included only as they occur in multiple purpose projects. Recreational problems are mentioned but not addressed in detail. The basic processes are the same as those causing flood control and navigation problems, but recreational problems require a considerable refinement to the spatial and temporal resolution in analytical techniques. Water quality aspects of sedimentation problems are extremely important in reservoir design; they should be addressed using water quality manuals. The physical problems, as opposed to water quality problems, are caused primarily by inorganic sediments. Although there is recent evidence that organic sediments affect water chemistry to the point of influencing the behavior of the clays, information to quantify that influence is not available.

5-3. Philosophy of the Sedimentation Investigation. The impact of the reservoir on stream system morphology should not be determined by comparing a "future condition with the proposed reservoir project in operation" to a static condition of the stream system depicted by either current or historical behavior. A more appropriate measure of impact is to develop a "base condition" by forecasting a future condition of the stream system without the proposed project, i.e., a "do-nothing condition." Then forecast a future condition for that stream system with the proposed project in operation to develop a "project condition." Then compare those two future conditions to determine the impact of the project on the stream system morphology. Notice, the "do-nothing condition" should contain all future changes in land use, water yield, sediment yield, stream hydraulics and basin hydrology except those associated with the proposed project.

a. System Response to Catastrophic Events. The floods in northern California and Oregon during December of 1964 so disturbed the stream systems that sediment yields, and river problems associated with them, were abnormally high even a decade later. These stream systems are in transition because of changes in sediment yield and water runoff hydrographs. Two points are significant:

(1) The water and sediment yields are the "Boundary Conditions" describing the amount of sediment that would enter a proposed reservoir project, and field data taken during the past decade would not be representative of future years on these streams because a catastrophic event has occurred.

(2) Secondly, if a reservoir project should be constructed on such disturbed streams, it should not be blamed for all changes which would occur during its operation because that stream system was already in transition prior to the construction of the reservoir. This point demonstrates: "always evaluate potential reservoir sites and report whatever transition may be in progress historically."

b. System Response to Normal Events. In the absence of field data, it is not possible to predict, with much accuracy, the sediment yield from such a catastrophic event as the December flood of 1964, but annual fluctuations in hydrology or sediment yield can cause a stream to be in transition. A data base can be acquired and future conditions can be predicted sufficiently well to minimize big surprises in this case.

Section II. Evaluation of the No-Action Condition

5-4. Indicators of Change in the Stream System. Trends, over the last decade or so, in any of the following parameters suggest the stream system is in a period of transition:

a. water yield from the watershed,

b. sediment yield from the watershed,

c. water discharge duration curve,

d. concentration of sediment,

e. size of sediment particles,

f. stage-duration curve,

g. depth, velocity, slope or width of the channel, or

h. bank caving

i. trends in "specific gage" plots (i.e., the stage for a constant discharge plotted versus time.)

Section III. Evaluation of Modified Conditions

5-5. Points of Caution. The following are sedimentation problems associated with reservoir projects. They should be forecast over the economic life of the project and reported via reservoir sedimentation studies.

a. Fallacies. Historically, some have pictured sediment as occupying a "dead storage" zone at the very lowest depths in the reservoir, and even described such space as "allocated for sediment retention", Figure 5-1. Others show deposits as if they occur only at the upstream end of the reservoir then vanish leaving clear water to the dam. A third fallacy can be seen in sketches which picture all deposition within the reservoir proper. Avoid these fallacies. Eventually, all reservoirs will fill with sediment.

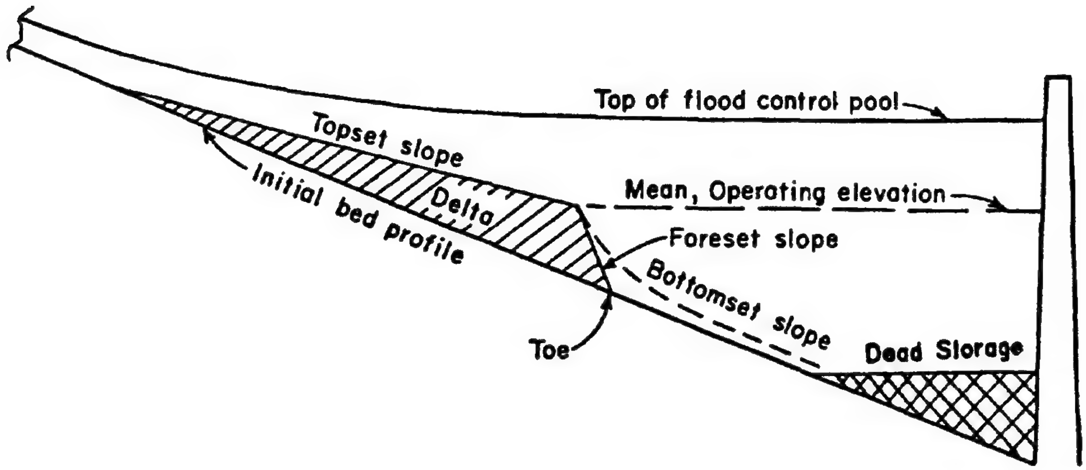

Figure 5-1. Incomplete Concept of Reservoir Deposition

The time can range from a single storm event to hundreds of years depending on sediment yield and reservoir operation. The sedimentation report should forecast sedimentation during the life of the project.

b. Topset Slope. A rule of thumb for the ultimate topset slope is that it should be 50 percent of the original stream bed profile. There is no physical reason for that value, however. Beware of any such assumption because the ultimate topset slope will be constructed by the river to be in regime with the river system. Numerical modeling is presently the most effective method for predicting that ultimate value.

c. Impact of Increased Stages Beyond Reservoir Limits. Sand and gravel will start to deposit upon reaching the backwater curve of the reservoir which is usually upstream from the reservoir boundaries. Those deposits increase the elevation of the bed surface profile which causes the water surface elevations to rise. Of course such increases will not continue indefinitely; the ultimate elevations will be in regime with the water-sediment hydrographs entering the reservoir from the upstream basin/sub-basins. As in the case of the topset slope, numerical modeling is the most effective method for

predicting the ultimate values of both the water surfaces and bed surface profiles.

5-6. Sedimentation Problems Associated with Reservoirs. The impact of sedimentation on reservoir performance can be measured by quantifying:

a. volume of deposition,

b. location of deposits,

c. rise in water surface elevations,

d. aesthetics of deposited sediment,

e. turbidity,

f. density current,

g. water quality aspects of sedimentation,

h. shoreline erosion,

i. shifting location of channels,

j. downstream degradation,

k. changes in downstream channel capacity,

l. local scour at the dam, spillway and stilling basin.

5-7. Impact of a Reservoir Project on Stream System Morphology.

a. rise in base-level, and associated aggradation, of the main stem upstream from the dam due to the reservoir impoundment,

b. fall in base-level of the main stem downstream from the dam due to modified hydrographs,

c. fall in base-level of the main stem downstream from the dam due to degradation of the channel bed,

d. changes in downstream channel capacity,

e. This is not an exhaustive list of problem areas. They are included because substantial resources have been expended to correct them at existing reservoirs; and consequently, they should be considered in all reservoir sedimentation studies. A reservoir will likely have additional problems which are unique to it and will need to be added. The following paragraphs illustrate why these problems have occurred.

5-8. Volume of Deposition. Land use change from natural forest to strip mining has so increased sediment yields that the useful life of some reservoirs will be reduced to a fraction of the 100-year design life unless action is taken to control the deposition problem. The volume of sediment material deposited in the reservoir delta IS NOT a function of the 100-year project life. That time period is an economic parameter, not a physical limitation. Consequently, delta growth will not cease simply because the project life has been reached. Eventually a new channel and flood plain will exist in the reservoir. Flood stages and the ground water table will reflect that condition adjacent to and upstream from the reservoir area.

5-9. Location of Deposits. This is a more precised term than "distribution of deposits". Location means the (x,y,z) location of deposits and not just deposition volume by project purpose. Also, the term "distribution of deposits" should refer to volume depletion by project purpose rather than spatial location of that deposit.

a. If volumetric reductions of reservoir storage space allocated for each project purpose represented the only problem associated with reservoir sedimentation, it would not be necessary to forecast the distribution of deposits in the reservoir. It would only be necessary to reassign reservoir elevations for the desired capacity as indicated by periodic resurveys. Such is not possible with hydropower machinery, however, because it is designed to operate within a prescribed head range.

b. Even if the total volume of sediment deposits is small, they may occur in locations where navigation, conservation storage, marinas, or other project features can not function as designed for project economics. Consequently, the spatial location must be predicted in addition to the elevation of deposits.

c. Deposition problems are often more severe on tributaries than on the main stem, and tributary locations are usually the most desirable for developing recreational facilities. Analysis is complicated by two factors: (1) the lack of basic sediment data because there is usually less on a tributary than on the main stem itself, and (2) the small size of the study area. However, recreation sites are a limited resource and their useful life should be evaluated in considerable detail so alternatives that maximize that life can be formulated.

d. Sediment deposits have raised water surface elevations (i.e., the stage-duration curve) sufficiently to raise the ground water table.

e. Aggradation affects not only the main stem, but also tributary channels and can reduce the capacity of, and even block, drainage structures along the channels at locations upstream from the normal operating pool elevation of the reservoir but within the backwater curve of the reservoir.

f. In existing reservoirs, the United States Fish and Wildlife Service is utilizing delta and back swamp areas in the propagation of wildlife. Since the characteristics of this delta area are so closely controlled by the operating policy of the reservoir, any reallocation of storage would need to consider the impact on present delta and back swamp areas. This represents a type of

problem that may be more important in the future if changing priorities among project purposes demand reallocation of storage in reservoirs.

5-10. Rise in Water Surface Elevations. Water surface elevations become higher for the same water discharge when both the sediment deposits and vegetation, which is attracted to those sediment deposits, combine to decrease hydraulic conveyance. These factors are significant because they produce higher water surface elevations after the project has been in operation for a while than were forecast for the initial impoundment. In both shallow and deep reservoirs, sand and gravel will deposit in the upstream direction thereby raising stages upstream from the reservoir area proper. The extent of these conditions can be calculated using numerical modeling, and such calculations should be reported because the amount of stage increase has proven to be significant within the life of existing projects.

a. Shallow Reservoirs. Deposits forming the delta may raise the water surface elevation, during some flows, above that of preproject elevations. Consequently, additional land must be acquired. That is, floods of equal frequency may cause higher water surface elevations after a delta begins to form than was experienced before the project was constructed even though the water discharge has been decreased by upstream projects. The controlling floods are often the more frequent events as opposed to the rare events.

b. Deep Reservoirs. The land taking elevation within the reservoir area is generally controlled by project purposes and not sedimentation.

c. Phreatophytes. Because of their high moisture content, reservoir deltas will attract phreatophytes which raise backwater profiles because they increase hydraulic roughness. In addition, the phreatophytes contribute to water use problems due to their high evapotranspiration rate.

5-11. Aesthetics of Deposited Sediment. Reservoir delta deposits often contain large, aesthetically undesirable, mud flats. Since reservoir operating rules are responsible for the deposit, a change in operating the project can expose a delta that was previously covered with water.

5-12. Turbidity. Turbidity has impacted strongly on the recreational usage of some projects. In addition, the presence of sediments in reservoirs has an effect on light penetration, thermal budget, nutrient budget, and benthic activity.

5-13. Density Current. The chemical state of the clay-water mixture can cause clay to stay dispersed creating a turbidity problem for recreational sites in the reservoir. On the other hand, it can cause the clay to flocculate and deposit in the the still water zones of the reservoir. Or, it can cause the water-clay mixture to form a density fluid, plunge and flow out the outlet works as a highly turbid discharge which affects recreational usage downstream from the reservoir. Density currents occur under conditions of high sediment concentrations, steep slopes (greater than 1 foot per mile), and large depths.

5-14. Water Quality Aspects of Sedimentation. Because other manuals address in detail water quality aspects of reservoirs, an extensive discussion is not presented. Project purposes often need a quality of water which requires the accurate accounting of sediment movement and the chemical and biological effect of the sediments, whether in suspension or deposited on the bed.

5-15. Shoreline Erosion. The shoreline erosion process stems from wind wave action, boat wave action and water surface fluctuation. Long distances of open water which are oriented with prevailing winds will allow the generation of large enough waves to make beach and shoreline erosion a potential problem. As the shoreline erodes, the eroded material tends to move to lower elevations thereby reducing the reservoir storage capacity allocated for specific purposes at those elevations.

5-16. Shifting Location of Channels. In navigation projects which utilize a combination of lock/dam structures and channel contractions work to develop a navigation channel, the channel contraction is designed for the upstream end of the navigation pools. As the delta develops, however, those works will need to be extended toward the dam, a condition occurring early in the life of some projects.

5-17. Downstream Degradation. Looking downstream from the dam, the predominant problems are associated with degradation of the main channel (i.e., a general lowering of the channel bed). Not only is the tailwater at the dam affected but also bridge crossings, pump intakes, diversion structures, local drainage structures, and recreational uses are affected. Consider the following conceptual model of the system behavior:

a. When a reservoir is first impounded, the hydraulics of a given water release (velocity, slope, depth and width) remain unchanged from conditions in the natural river.

b. However, the reservoir has trapped sediment material, especially the bed material load. This reduction in coarse sizes of sediment allows the surplus energy in the flow to entrain material from the stream bed. That produces a degradation trend.

c. Degradation refers to the general erosion of the channel bed over a substantial distance and for an extended period of time such that the elevation duration curve trends downward. It is different from the local scour that will occur at a structure.

d. The degradation trend will start at the dam and migrate in the downstream direction as time passes. The downstream migration causes a decrease in channel slope which helps to reduce velocities and, therefore, to retard the degradation process.

e. Several other factors are also working to establish the new equilibrium condition in this movable boundary flow system. The bed surface is becoming coarser which shields particle sizes beneath it. Discharge hydrographs are not peaking as high as preproject conditions. Tributaries are contributing more sediment than under preproject conditions because the base-

level has been lowered.

f. As the bed degrades, the finer sediment sizes will move out faster than the coarser sizes. The bed surface will become coarser with time and consequently will move at slower and slower rates until finally, movement under normal reservoir releases will cease.

g. Coarse gravel and cobbles move only during the more extreme flood discharges and some reservoirs eliminate such flood events.

h. Degradation of the main channel plus the modified discharge hydrographs from the reservoir combine to produce a base-level lowering along the downstream channel. The potential energy gradient at the downstream end of each tributary will increase which results in degradation migrating up the tributary. That supplies additional sediment to the main stem which tends to offset the effect of the reservoir and arrest degradation of the main channel. However, it can produce tributary degradation with associated geotechnical failures of banks.

i. The time required for degradation problems to become noticeable depends on the size of sediment grains in the stream bed and banks. That is, fine sands will move at the water velocity so degradation is quite rapid in such material.

j. The extent of degradation is complicated by the fact that the reservoir also changes the water discharge duration curve. This will impact for great distances down stream from the project because the existing river channel reflects not only peaks but also the historical phasing between flood flows on the main stem and those from tributaries. That phasing will be changed by the operation of the reservoir.

5-18. Changes in Downstream Channel Capacity. Early in the life of many projects, bank full capacity of the channel has become less than it was before the dam was built. Consequently the reservoir can not discharge the rate of water needed to maintain the reservoir operating rules used for project design studies. Two factors are believed to be responsible: the flow duration curve is modified by reservoir operation such that the dominant discharge becomes smaller with the project than it was without it. Consequently, a smaller channel develops. The second factor results from the continuous releases from the reservoir. Vegetation will be encouraged to grow at lower elevations along the channel resulting in higher bank roughness plus sediment deposition in the vegetation. Both factors contribute to a loss in conveyance for channel flows. Design studies must account for that reduction in flood releases. The degradation trend reverses the decrease in channel capacity as time passes, but downstream movement is usually slow.

5-19. Local Scour at the Dam, Spillway and Stilling Basin. Local scour is always a problem at hydraulic structures. Abutments are the weakest zone and should be designed to either prevent flow from short-circuiting the overbanks and cascading down the tie between the structure and the channel bank line or accommodate such a flow path. Another critical zone is the emergency spillway. These are usually designed for infrequent, if ever use, and flow is

left to seek a path of return to the channel. Make sure that path is as long and tortuous as possible. In the late 1970's emergency spillways were overtopped at two reservoirs near major metropolitan areas. Although the discharge peaked at only 10% of the spillway design discharge and flow continued for a limited duration, extensive erosion of the land occurred as flow sought a return path to the channel. In one of those cases the erosion pattern was that of a waterfall, or head-cut, which moved in the upstream direction. Unlike the description of a head-cut on a tributary, this head-cut got taller as it moved upstream toward the spillway. It came within a few hundred yards of reaching the apron of the stilling basin before the overflow stopped. Once such an event is underway all one can do to it is take pictures. Therefore, give careful attention to safety when reservoirs are located upstream from urban areas. Major failures can occur in a single flood event. Land use change during the life of the project should be a major consideration downstream from such structures.

Section IV. Levels of Sedimentation Studies and Methods of Analysis

5-20. Staged Sedimentation Investigations. The basis for staged sedimentation studies is given in Chapter 1. Words of caution to those who follow the staged concept are "be prepared to modify basic project features as cited in Chapter 1 if the preliminary assessment is in error."

a. Staged sedimentation studies should adopt the "safety factor-project impact" concept in which a safety factor from 1.5 to 2 times the best initial estimate of the sediment impact is used to develop an impact on project costs. If the problem is sediment deposition in the reservoir the sediment yield should be adjusted by the safety factor. If the problem is bed degradation downstream from the dam, or any where in the study area, the safety factor concept should be applied to stability coefficients and transport capacity. Providing such an impact does not affect basic go/no-go decisions about the project, the sedimentation study can be staged and refined as the project moves through planning and design stages. However, if sediment problems appear to dominate project design and economics, the staged concept should be avoided in favor of a more defendable sedimentation study based on field data.

b. Two stages are proposed for a reservoir sedimentation study: the Sediment Impact Assessment and a Detailed Sedimentation Study. The objective is the same in each stage. The scope of the study is the same in both, but the depth of study is controlled by project formulation economics in the impact assessment whereas in the detailed study it is controlled by the technical details of the problems.

5-21. Sediment Impact Assessment. The purpose of the sediment impact assessment report is to convey to reviewing authorities (1) the amount of effort expended to date in investigating sedimentation problems; (2) the amount and type of field data available for the assessment; (3) the anticipated impact of sedimentation on project performance and maintenance, and (4) the anticipated impact of the project on stream system morphology. This assessment is expected in the initial planning document with amplification as necessary in subsequent reports. It should recommend

additional studies, if needed, and serve as the basis for preparing the sediment Studies Work Plan described in Chapter 2. A negative report is as important as one identifying problems.

5-22. Scope. This report should discuss, at a minimum, reservoir sedimentation problems and the impact of the project on stream system morphology. It should present the data itemized above in as complete form as it is available from office files and the field reconnaissance.

5-23. Approach. Usually field data are not available for this level of study. The approach is to use data from office files, from references and from regionalize data gathered at nearby projects to predict what will happen at the one under study. As in physical modeling, a procedure to assess similitude between projects is needed. The following is considered an acceptable level of similitude: demonstrate the reservoir purposes are similar, the water yield and sediment yield unit rates from the basin are similar, the sediment properties are similar, and reservoir operating rules are similar.

a. Always consider the occurrence or absence of extreme hydrologic events when using or transferring historical data. Develop a "safety factor" for the anticipated sediment yield rate and establish resulting project performance.

b. Acceptable analytical techniques for making the necessary calculations are summarized in appendices of this manual and are referenced in the topic statements below.

5-24. Topics to Report. The following list of topics not only suggest items to include in the sedimentation report but also show the general sequence of tasks for performing the study.

a. Basic Background Information. Report the pertinent data for the dam:

(1) Basin and site location maps. The general geographical location and site location for the dam are needed. Study area and reservoir maps are needed to develop the boundaries of the project area and the boundaries of the study area.

(2) Project purposes and life. A statement of the project purposes and storage allocations for each is needed. In flood control reservoirs the project life for sedimentation is 100 years. In navigation projects a 50 year life is used.

(3) Design details for the dam. Only the proposed spillway crest elevation is needed for this level.

(4) Reservoir storage allocations. The proposed elevations for storage pools are major factors in establishing the location of the reservoir delta.

(5) Stream bed profiles through the study area

(6) The rational for establishing study area boundaries (This includes establishing the sources of water, sources of sediment, presence of upstream projects, hydraulic and sediment conditions at boundaries of project, and the impact of the project on those boundary conditions)

b. Results of the River Morphology Study.

(1) Land use. Report historical and probable future land use in the basin. Knowledge of historical land uses in the basin will help in understanding historical sediment records. Predicted future land use is essential for estimating future sediment yield. (Chapter 3)

(2) Annual water yield. Annual water yield is necessary but 90 percent of the sediment is transported during the flood events. Therefore, if information is available for floods, present it also. Both historic and future conditions should be estimated. (Chapter 3)

(3) Erosive mechanisms and soil types. Consider the possibility that erosive mechanisms are associated with land use. Report the erosive mechanisms and soil types. Where sheet and rill are the dominant erosion mechanisms, unit values based on drainage area (i.e., tons per acre per year) are appropriate for estimating sediment yield from the basin. If the soil is sandy, the proximity of the sand source to a water course is as significant as the surface area in determining the delivery to the channel. Consequently, yield from gullying and bank erosion are probably better correlated with miles of channel in the basin than they are the surface area.

(4) Sediment yield analysis. The suggested topics to include here are given in the chapter on sediment yield. Total sediment yield into the reservoir, during the project life, is necessary. If refinement is needed determine what percentage of that total is made up of silt and clay. (Chapter 3)

(5) Sediment properties of channel. At a minimum, describe the type of sediment material forming the stream bed and banks from records and photographs made during the field reconnaissance trip, (Appendix E). A few samples of the bed material are desirable.

c. Analysis of Reservoir and Watershed Parameters.

(1) Trap efficiency of reservoir and volume depletion, (Appendix F).

(2) Specific weight of deposits, (Appendix G).

(3) Estimated depletion of reservoir volume by pool elevation, (Appendix H).

(4) Estimated elevations for real estate requirements (Water Surface Profile Calculations with sediment deposits.)

(5) Predicted effect of sediment deposits on future river stages upstream from reservoir (Numerical modeling)

(6) Report the possibility of turbidity in the reservoir. Turbidity is associated with soil type. For example, soil types which erode as colloidal particles will create turbidity problems in the reservoir.

(7) Possibility of bank erosion. A soils map will provide soil types at reservoir operating levels. A assessment can be made as to the potential for shoreline erosion.

(8) Possibility of a density current.

d. Analysis Downstream from the Dam.

(1) Modified stage duration curve at dam. Get this graph from the modified flow duration curve and use it to indicate base-level lowering due to regulation.

(2) Degradation of the channel bed. Use this study to estimate lowering of the tailwater rating curve for the stilling basin and hydropower head, (Appendix J).

(3) Predicted future tributary degradation. Combine the modified stage duration curve with degradation predictions on the main stem to forecast the need for stabilizing tributary degradation problems. Adapt the method in Appendix J to estimate the upstream limit of degradation.

5-25. <u>Detailed Reservoir Sedimentation Study.</u> The purpose of the detailed reservoir sedimentation study is given in Chapter 1.

5-26. <u>Scope.</u> The breadth of a detailed study encompasses the same problems identified in the impact assessment but is greater in depth because of the need to calculate rates and volumes of erosion, transportation and deposition in both time and space and to propose and rank alternative designs.

5-27. <u>Method of Analysis.</u> This level of study is designed for numerical modeling techniques because the analysis of the data set is more labor intensive than one can afford manually. Numerical modeling techniques are structured entirely for computer solution.

5-28. <u>Approach.</u> The amount of data that has to be analyzed includes all the basic geometric and hydraulic data required for water surface profile calculations plus data describing the size and gradation of sediment material in the stream bed and banks, the size, gradation, and amount of inflowing sediment material and the water discharge hydrograph. In addition, long periods of hydrograph record are generally utilized since sediment studies attempt to predict trends throughout the project life. The number of calculations is extremely large. For example, predicting deposition in a shallow reservoir having a 50 year design life can require the calculation of 1000 to 6000 water surface profiles plus the routing of sediment material through the reservoir for the water discharge associated with each of the profiles.

a. Shallow Impoundments. For reservoirs which do not modify the hydrographs significantly, set the inflow boundary upstream from the reservoir and out of the influence of it and set the outflow boundary at the downstream end of the downstream study reach. The dam will be an internal control point where stages are controlled, and the sediment discharges passing the dam will be feed directly into the downstream reach.

b. Deep Impoundments. For reservoirs which modify the water discharge hydrographs, break the numerical model at the dam. Use the inflowing hydrographs and operating rule for boundary conditions for the upstream model, but use the modified hydrographs and sediment discharges passing the dam for inflows to the downstream model. The downstream boundary of the downstream model will be a stage discharge rating curve or a stage hydrograph. It should be beyond the influence of degradation.

5-29. Topics to Report. Topics suggested for the Detailed Sedimentation Study are shown in the following sub-paragraphs. Note that many are the same as in the Impact Assessment, but they are in more detail.

a. Basic Background Information. Report the pertinent data for the dam:

(1) Basin and site location maps. The general geographical location and site location for the dam are needed. Study area and reservoir maps are needed to develop the boundaries of the project area and the boundaries of the study area.

(2) Project purposes and life. A statement of the project purposes and storage allocations for each is needed. In flood control reservoirs the project life for sedimentation is 100 years. In navigation projects a 50 year life is used.

(3) Design details for the dam. Plan and elevation views of dam, outlet works and spillway.

b. Analysis Upstream from the Dam. The volume and location of deposits; new storage curves at selected future dates; elevations for real estate requirements; the effect of sediment deposits on future river stages upstream from reservoir on the main stem and tributaries; and navigation dredging requirements will come directly from the numerical model output. The following data are required

(1) Reservoir and river geometry. Cross sections and stream bed profiles through the study area

(2) Sediment properties of bed material

(3) Top of rock profile

(4) Water inflow hydrographs. Annual water yield is necessary but not sufficient for detailed reservoir sedimentation studies because 90 percent of the sediment is transported during the flood events. Therefore, provide water discharge hydrographs also. Both historic and future conditions should be

developed for each subbasin in the model.

(5) Inflowing sediment concentrations and properties.

(a) Sediment concentrations. The inflowing sediment concentration is needed for each water discharge in the hydrograph. Rather than constructing a concentration hydrograph, use the sediment discharge rating curve obtained from measurements of sediment concentrations. This should be after adjusting the curve for future conditions when analyzing proposed project conditions.

(b) Sediment properties. Sediment properties refer to size, density, shape, and chemistry of individual particles of sediment. Next to concentration, the most significant parameter in determining storage depletion in a reservoir is particle size. That is determined by analyzing suspended sediment samples. In addition to size, particle density, shape, and electrochemical activity is required. Suspended sediment samples are needed for a wide range of water discharges.

(c) Adjustment for future land use. Knowledge of historical land uses in the basin will help in understanding historical sediment records. Predicted future land use is essential for estimating future sediment yield. Consider, also, the probable erosion mechanisms and how they will change with land use.

[1] Where overland flow, gullying, and channel bank caving are the dominant mechanisms, unit values are not sufficient to determine basin yield. Divide the sediment into wash load and bed material load categories. Use unit sediment yields for the wash load portion, but calculate the bed material discharge using transport theories and compare that result to the unit production quantities of sands.

[2] Soil type will greatly influence erosion rate, and thereby, sediment yield from the basin. That is, once silts and colloidal particles become detached the particles move easily through the water courses. Sandy soils detached by sheet or rill mechanism, on the other hand, are likely to settle out a short distance away. Consequently, proximity of the sand source to a water course is as significant as the surface area parameter in determining the delivery of sands.

(6) Operating rule curve. The operating pool elevations and rule curve provide the downstream control for sediment routing through the reservoir.

(7) Specific weight of deposits. Whereas sediment properties refer to the individual particles, specific weight of deposits refers to the bulk property of the mass of the sediment deposit. It is expressed as pounds/cubic foot, dry weight, and is the key for converting units between weights and volumes. Such conversions are common because sediment movement computations are made in mass units and reservoir storage depletion requires a volume unit, (Appendix G).

(a) The major factor affecting specific weight of deposits is particle size. Coarse sediments such as sands and gravels deposit at a density very near their ultimate density.

(b) As particle size decreases into the silts and clays, secondary factors become important. Silt and clay will deposit as a "fluffy" mass (i.e., at a low specific weight) and as time passes that deposit will consolidate. Time, the drying due to reservoir draw-down, and the overburden pressure of more deposits are factors determining the rate of consolidation. A method is available to estimate the initial specific weight and the consolidation coefficients so future conditions can be predicted.

(c) Elevation-capacity curve. The relationship developed for hydrologic studies which shows initial volume in the reservoir versus elevation at the dam is needed. The volume of storage allocated for each project purpose should be shown on that relationship. These should be reconstituted by the sediment model to confirm the geometry has modeled reservoir volumes adequately.

(8) Topics not addressed by the numerical sediment movement model are density currents, turbidity, and shoreline erosion.

(a) Report the possibility of turbidity in the reservoir. Turbidity is associated with soil type. For example, soil types which erode as colloidal particles will create turbidity problems in the reservoir.

(b) Possibility of a density current.

(c) Possibility of shoreline erosion. A soils map will provide soil type at reservoir operating levels. A assessment can be made as to the potential for shoreline erosion from estimated wind wave heights, erosive forces and riprap requirements.

c. Analysis Downstream from the Dam. The reservoir causes this portion of the system to be sediment starved. Classical transport theory would indicate catastrophic consequences, and such will likely occur only if sediment concentration is the only variable affected by the reservoir. However, the water discharge-duration curve, hydraulic roughness and local inflow of sediment from tributaries are all affected by the reservoir and are factors in the degradation process. Report the following:

(1) Rationale for limits of study area. The study area should start at the dam and go, uninterrupted, to a stable control such as a bed rock outcrop or some other hard point across the channel. Laterally, the study area should extend up each tributary where degradation is not arrested by bed rock or some other resistant material. Maps showing study area boundaries are needed. They should show all points where flow enters or leaves the study area and all structures, either on or across the streams, in the study area.

(2) Selection of geometry. Justify the cross sections and reach lengths used for water surface profile computations on the main stem and up each tributary where significant degradation problems seem likely.

(3) Hydraulic roughness. The n-values will change with time and should be related to grain size and sediment transport.

(4) Sediment inflow. Justify the sediment discharge, by particle size, passing the dam.

(5) Bed material gradation. Justify the gradation of the bed surface and the gradation at depths beneath the bed surface through the study area. Top of rock or clay profiles are needed.

(6) Tributary data. Justify the discharge of the bed material load, by grain size class, for each major tributary. As in the case of upstream data, land use change should be considered in developing this data.

(7) Hydrologic data. Show the modified discharge hydrographs for dam releases and on each major tributary at the study area boundary. Water temperature is needed at each inflow point. Justify the stage-discharge relation used for the downstream boundary of the degradation study reach.

Section V. Reservoir Sedimentation Investigation Program

5-30. Reservoir Sedimentation Investigation Program. This is a post-construction activity which monitors for sedimentation problems resulting from the reservoir. The Corps of Engineers cannot control land use sufficiently well to control future sediment yield,and it is imperative that the rate and location of sediment deposits be known. Checking for aggradation of channels upstream from the reservoir and degradation of channels downstream from the dam is also included in this monitoring program. To insure that information is available for other design studies and to provide general information on reservoir sedimentation, a systematic, reservoir sedimentation investigation program is required at each reservoir. The program is described in this manual in Appendix K, "Reservoir Sedimentation Investigation Program". It is to be implemented even if the Sediment Impact Assessment study identified no adverse sediment effects.

Section VI. Debris Basin Design

5-31. Debris Basins. Debris basins, sometimes called sediment retention basins, are reservoirs designed to trap sediment and debris. In this usage, debris refers to the assortment of sand, gravel, cobbles, boulders, logs and other large pieces of material that deposit in a channel causing flood flows to spill out before design conditions are reached. Generally, debris basins are used where channel slope becomes flatter, for example, where a stream leaves hills and flows across a flood plain. The need is easily identified by noting channel meander and braiding patterns on aerial photographs.

5-32. Design Considerations. Debris basins are growing in popularity; however, little work has been done to aid in their design and evaluation except in the southern California area, and that work is not portable to other locations.

a. Design Guidelines. The Federal Highway Department has published guidelines for sedimentation basin design, reference [53].

b. Safety. It is imperative that project safety be a key factor in sizing the basin. Project safety requires not only design flood considerations but also the proper consideration of conditions anticedent to a design flood. Also, the debris basin should function so if a flood should occur which exceeds the design flood, the project will not make conditions worse than would have occurred without the project.

c. Location. Debris basins are placed upstream from flood protection or navigation channels. Access and shape are important considerations because they affect clean-out and trap efficiency, respectively.

d. Basin Size. They are usually small and designed to be cleaned out from time to time. However, the size is not arbitrary. It must be justified by project economics and available sites. Some basins are sized for only one or two major storms. Others may have a 50 or 100 year capacity.

e. Topset Slope. The volume available for sediment storage in the debris basin is considerably different from the horizontal planes used in water storage calculations. A delta will form in these basins just as it does in a reservoir. Starting at the crest of the dam the topset slope of the delta can be estimated to be 50 percent of the original valley slope. That is adequate for the impact assessment, but numerical modeling should be used to calculate a topset slope for the detailed sedimentation study. It will often exceed the 50% approximation. Of course, trap efficiency of the basin decreases as it fills, and that will determine how much material can be stored before removal is required.

f. Sediment Yield. Sediment yield estimates for debris basin design should include two kinds of hydrological events: the normal, long term records and the design flood events. Long term average sediment concentration records should be used for the long term hydrologic events. The long term average concentration is determined from the best fit line through the log-log plot of water discharge versus sediment discharge. It assumes flood data are available and low flow data were not extrapolated up to the range of water discharges in the design flood peak.

g. Analysis by Particle Size Class. Sediment yield studies for debris basin design always require grain size data. Methods which seem to ignore that data, such as Tatum, actually have it built into the coefficients and procedures. They should be used only in the region for which they were developed.

h. Single Event Sediment Concentrations. The best fit line on the water discharge-sediment concentration plot should be adjusted upward to develop a concentration for large floods. For example, in a flood having a chance, or less,1 or 2% , the sediment concentrations may exceed long term averages by a factor of 2 or 3.

i. Sediment Discharge Curve Extrapolation. If flood measurements are not available, use the transport capacity approach described in Chapter 3 to extrapolate the water-sediment discharge relationship. If the concentration of fines exceeds 10,000 ppm, (10063 mg/l), they will begin to increase

transport capacity. By the time they reach 100,000 ppm (106,640 mg/l) that influence can be as much as a factor of 10 or 20 times the normal transport capacity.

j. Staged Design Studies. Usually the debris basin design can be staged as discussed above for the sedimentation investigation, but a detailed sedimentation study is recommended by the time the feasibility level of project formulation is reached in projects where debris basins are required.

k. Embankment Height. The height of the top-of-embankment above the spillway crest should be designed for the condition when the active flow channel has become the width of the inflowing channel and is located adjacent, and parallel to, the embankment. Calculate the height of embankment using a slope equivalent to the valley slope transporting sediment into the basin and the distance from the spillway to the end of embankment. Add freeboard and velocity head to that height as appropriate to turn the approaching flow. That will accommodate an energy loss for a flow that is the width of the natural river channel and flowing along the face of the embankment.

5-33. Design Method. The trap efficiency of the basin can be calculated using numerical sediment models such as HEC-6 provided the proper skill is used in defining the geometry for the hydraulics calculations. The objective is to calculate the reduction in sediment discharge by particle size so the outflowing load curve is defined as a function of basin capacity. The end product will be a size and shape of basin to provide the required storage capacity for sediment for the period between clean out operations.

a. Defining the Geometry. Initially flow is 3-dimensional; however, the rapid deposition of sediment seems to cause a rapid return to the 1-dimensional channel hydraulics problem. Therefore, a 1-dimensional numerical model is proposed provided the following flow field-sediment deposition concepts are followed.

b. Conveyance Limits. The inflowing water-sediment mixture will not expand instantaneously.

c. Longitudinal Profile. Deposition will occur quickly for sands and gravels and the location will start near the inlet.

d. Lateral Shape of Deposits. Deposition of sands and gravels will first fill the channel under the expanding jet until the loss in conveyance causes the jet to deflect to one side or the other.

e. Sorting by Particle Size. The design must be analyzed by particle size. Whereas the coarse particles settle out under the expanding jet, 1 to 2 fps is enough energy to keep the fines in suspension. Fines in the slower velocity water adjacent to the jet will be entrained by eddys and deposit toward the sides of the basin if at all. If the deposition of fines is of primary importance, a 2-Dimensional Model such as TABS-2 is recommended.

f. Channel Regime. As the basin fills the fluid jet will tend toward the same width as the natural channel width rather than remaining a uniformly

distributed velocity across a wide basin.

Chapter 6

Model Studies

6-1. General. Physical and mathematical models are useful tools in the solution of sedimentation problems. A physical model study is in order when existing design criteria are inadequate to meet the required level of confidence for a specific project. The large number of variables that effect sediment transport, together with the infinite variety of boundary conditions with hydraulic structures and natural channels, often makes it impossible to develop comprehensive optimal relationships to use as the basis for design. Consequently, many hydraulic phenomena are studied by means of physical models, using the basic principles of similitude to correlate model and prototype behavior. Physical model tests are generally desirable where local scour or sediment deposition could endanger the functionality of a hydraulic structure or river modification. Physical models provide a means for checking project performance and devising modifications to obtain the best possible design at minimum cost. Mathematical models are applicable when the sediment behavior can be predicted analytically. Mathematical models generally require more data to calibrate and verify than physical models, but once this is accomplished, it becomes relatively simple to test various modifications and design proposals. The design engineer must be familiar with the theoretical background of the mathematical model, including its limitations and applications; he must avoid the tempting "black box syndrome" which may yield computer output impressive in volume but meaningless in substance. Physical and mathematical models should be used to supplement, but not replace, theoretical knowledge, good judgment, and experience.

6-2. Undistorted Physical Model. Undistorted physical models are generally used to determine local scour patterns downstream from hydraulic structures. Usually the bed material cannot be scaled down as required by laws of similitude, so results are generally qualitative rather than quantitative. These qualitative results can be used to compare the local scour effects at various designs of outlet works, bridge piers, abutments, spur dikes, protective aprons, training walls, and sediment diversion and exclusion structures. The theory of physical model design is discussed in detail in several publications [9], [15], [3], and [70]. For sediment models, where the gravity force dominates the flow, similitude will require equality of Froude number in the model and prototype. The following Froudian scale relations (prototype/model) apply to undistorted models.

Manning's n	Length	Area	Volume	Time	Velocity	Discharge
$Lr^{1/6}$	Lr	Lr^2	Lr^3	$Lr^{1/2}$	$Lr^{1/2}$	$Lr^{5/2}$

6-3. Model Scales. The length ratio Lr is the prototype-to-model ratio Lp/Lm. The transfer relations above are based on equal force of gravity and density of fluid in model and prototype. Physical models must be designed such that turbulent flow will prevail with the model velocities and depths in order that essential flow patterns are preserved. Model Reynolds Numbers greater than 1800 are generally required to ensure turbulent flow. Since the

model Reynolds number will always be smaller than the prototype Reynolds number, there will be some scale distortion of certain phenomena such as zones of separation, wave dissipation, flow instability, and turbulence in the model. Particular care should be taken in interpreting those effects that are known to be strongly dependent on viscous forces. It is frequently impossible to preserve similitude with respect to size and weight of bed material in physical models. However, several investigators have concluded that the effect of bed material size on scour depths is insignificant. Amad [1] found that bed material size effected rate of scour around a spur dike but had no effect on ultimate scour depth. Liu et al [38] concluded that bed material size had an insignificant effect on the depth of local scour at bridges. Laursen [36] agreed as long as there was sediment transport into the scoured region. Vanoni [2] reached the same conclusion based on a thorough review of available references. These investigations increase confidence in results obtained from physical models where bed material similitude is not maintained. However, there remains insufficient prototype-to-model comparisons to prove conclusively that bed material size is insignificant in local scour problems and model results should be considered qualitative.

6-4. Distorted Physical Models. Movable bed physical models of river channels, flood ways, harbor, and estuaries often require a distortion of the vertical scale in order to ensure movement of the model bed material. Vertical scale distortion also allows for measurable depths and slopes as well as ensuring turbulent flow in the model. The scale relations for distorted models are given in reference [3]. If the bed slope is made equal to the energy slope ratio, the slope ratio will also be equal to the amount of model distortion.

$$Sr = Yr / Xr \qquad (6\text{-}1)$$

where:

Yr = the vertical scale ratio
Xr = the horizontal scale ratio, prototype to model.

The Manning equation can then be used to obtain a roughness criteria for model design [15].

$$nr = Rr(2/3) / Xr(1/2) \qquad (6\text{-}2)$$

For a wide channel the equation above reduces to

$$nr = Yr(2/3) / Xr(1/2) \qquad (6\text{-}3)$$

The required roughness in the model can be computed by equation (6-2) and used as a guide in designing the model. To ensure sediment movement at low model velocities, it is often necessary to use a model bed material lighter than sand. Coal dust (Specific Gravity = 1.3 approximately) and plastics (Specific Gravity = 1.2) are common model bed materials. Scale distortion in movable bed models presents several problems. Vertical distortion may increase the bank slopes beyond the angle of repose so that they will no longer stand. One remedy is to make the banks rigid, but this can only be done if the banks are known to be stable. Scale distortion also increases the longitudinal slope of

the river making it necessary to increase model roughness. However, roughness is primarily a function of bed forms and cannot be arbitrarily adjusted. Vertical distortion also distorts the lateral distribution of the velocity. This creates simulation problems at confluences, bifurcations, and sharp bends. The problems related to vertical distortion generally limit movable bed models to mild sloped streams where the distortion ratio should be limited to 3. In special cases the distortion ratio could be as high as 10. In harbor and estuary models greater distortion is permitted due to the relatively small prototype sand slopes and very mild water surface slopes. The choice of scales and bed materials for movable bed models is largely based on the experience and judgment of the modeler. At the Waterways Experiment Station coal dust is frequently chosen as the bed material. Model velocities ranging between 0.3 and 1.0 ft/sec are required to simulate bed material movement. This velocity criteria is used to select a vertical scale. The slope of the model is then determined using the Manning's equation with a roughness coefficient of 0.018 for coal dust. The horizontal scale is determined from

$$Xr = Yr / Sr \tag{6-4}$$

The time scale governing the fluid flow in the model will probably be different from the time scale governing sediment movement. This means that the hydrograph applied to the model will have to be reduced by model operation. During the model verification process, adjusted historical hydrographs are run through the model until historical bed changes can be reproduced. The adjusted hydrograph may require different time scales for low discharges than high discharges because of the nature of the model bed material. For instance, coal dust moves rapidly from little movement to violent movement with small increases in tractive force so that the time scale would be increased for low stages and decreased for high scale in order to simulate prototype bed movement. The verification of the movable bed model is very important due to the absence of quantitative similarity. Once the model and its operations is adjusted so that it accurately reproduces known bed configuration changes, then there is ground for confidence in model predictions of future events.

6-5. Numerical Models. The computer program HEC-6 "Scour and Deposition in Rivers and Reservoirs" is used throughout the Corps of Engineers to set up numerical models of river systems. The application, data requirements, and theory behind this program are discussed at length in the references [24], [52], and [51]. Numerical models, like physical models, must be verified and calibrated if they are to be effective predictors in river systems. It may be tempting to feed data into a computer program such as HEC-6 and consider the results as reliable. However, mobile boundary computer Programs are not simple extensions of fixed boundary hydraulics, as numerous complex factors are involved which are not fully understood. Verification and calibration are essential to demonstrate the programs are simulating the prototype.

6-6. Calibration. Ideally, any quantitative analysis should be based on predictive equations that have been calibrated and verified. The calibration process consists of taking known physical conditions and adjusting coefficients and representative values needed for the one dimensional average

approximations to reproduce measured changes. After the predictive equations have been calibrated, the model should be verified by testing the behavior against data not used in the calibration. That step is not always possible, and when it is, careful attention to the boundary conditions are required. That is, do not expect to reconstitute specific field measurements with a model which has a general calibration. Moreover, do not expect to reconstitute a specific period using representative boundary condition developed from some other flow record.

6-7. Prediction. Models that have been calibrated can then be used to predict future conditions with a degree of certainty that is as reasonable as the predicted, future boundary conditions will permit.

6-8. Interpretation of Results. Results from numerical as well as physical models should be interpreted by comparing the results from a plan test with those for a base condition. The base condition is the predicted future with no project. All input data should be the same in the two runs except the variable being tested. For example, deposition and degradation due to a dam should be compared with sedimentation in that reach of river if no dam is built to determine problems resulting from the dam. Therefore, the Base Test Conditions would come from simulating sedimentation for the entire length of stream in the study area during the project life for a no dam condition. The Plan Condition would be determined by installing the dam and re-running the simulation. The impact of the dam is determined by comparing those two results.

6-9. Scour and Deposition in Rivers and Reservoirs (HEC-6). The most commonly used movable bed computer program for 1-dimensional computations is HEC-6. This program is designed to analyze scour and deposition by modeling the interaction between the water-sediment mixture, sediment material forming the stream's boundary and the hydraulics of flow. It simulates the ability of the stream to transport sediment and considers the full range of conditions embodied in Einstein's Bed Load Function plus silt and clay transport and deposition, armoring and the destruction of the armor layer. It has no provision for simulating the development of meanders or specifying a lateral distribution of sediment load. The program can be used to determine both the volume and location of sediment deposits in reservoirs. Degradation of the stream bed downstream from dams can be determined. Long term trends of scour and deposition in a stream channel as a result of channel modification can be simulated. Channel contraction required to either maintain navigation depths or diminish the volume of maintenance dredging can be studied, but not in the detail obtainable from movable-bed physical model studies. The influence that dredging has on the rate of deposition can be simulated, and scour during floods can be investigated.

6-10. Open Channel Flow and Sedimentation (TABS-2). This is a 2-dimensional, finite element calculation of the Reynold's form of the Navier-Stokes equation for hydraulic parameters, linked, by a similar solution, with the convection-diffusion equation for sediment transport using an uncoupled computation scheme. All non-linear terms are present allowing the computation of eddys and separation zones. Like HEC-6, this system of computer programs is available for Corps Wide use. It is maintained and supported by Waterways

Experiment Station. More information on TABS-2 is available in reference [67].

6-11. CORPS. The Waterways Experiment Station maintains a system of computer programs for hydraulic design. The system is called CORPS which stands for Conversationally Oriented, Real-time Program Generating System. It is documented in the Waterways Experiment Station report by that same name, [66].

a. Scope. These programs cover the range of problems presented in Hydraulic Design Criteria: spillways, stilling basins, outlet works, locks, closed conduit flow, open-channel hydraulics, stable channel design, and sediment transport. However, new programs are added in response to field office requests so use the on line documentation system for current information.

b. Access. Access to CORPS is available via the district's computer, the Corps wide contract computer service or the Waterways Experiment Station computer. Access information can be obtained from the district Automatic Data Processing (ADP) contact, the Waterways Experiment Station ADP Center or the Chief, Hydraulic Laboratory, Waterways Experiment Station.

c. Documentation. Once on line the following information can be acquired:

(1) Description of "CORPS."

(2) Listing of the available programs by category,

(3) Brief description of any of the programs in the system,

(4) Execute demand for any of the programs.

d. The sediment group. One of the groups in the CORPS system is sedimentation. Sediment transport, flow resistance over movable beds, stable channel design, riprap design, and particle settling velocities programs are available with several examples being shown in the following list.

H0011 KINEMATIC VISCOSITY OF WATER, EFFECTS OF TEMPERATURE

H0910 COMPUTATION OF PARTICLE FALL VELOCITY BY SHAPE FACTOR

H0920 TOTAL SEDIMENT TRANSPORT RATE IN SAND BED STREAMS BY COLBY'S METHOD

H0921 BED-LOAD TRANSPORT IN RIVERS BY EINSTEIN'S PROCEDURE

H0922 TOTAL SEDIMENT LOAD BY MODIFIED EINSTEIN PROCEDURE

H0923 BED LOAD TRANSPORT RATE BY MEYER-PETER MULLER'S METHOD

H0924 COMPUTATIONS OF SEDIMENT DISCHARGE IN RIVERS BY SHEN AND HUNG'S METHOD

H0925 TOTAL SEDIMENT DISCHARGE BY YANG'S METHOD

H0926 SAND DISCHARGE BY TOFFALETI'S METHOD

H0941 STABLE CHANNEL DESIGN

H9110 FLOW RESISTANCE OVER MOVABLE BEDS BY EINSTEIN'S METHOD

H9111 FLOW RESISTANCE BY THE METHOD OF WHITE, PARIS AND BETTESS

H7010 RIPRAP REQUIREMENTS FOR OPEN CHANNELS

H7220 EROSION AT CULVERT OUTLETS AND RIPRAP REQUIREMENTS

e. Category "A." Each program has been checked to be as foolproof as possible in compliance with Category "A" quality control. Documentation, prepared according to Category "A" standards as established by the Office, Chief of Engineers (OCE), is available for each program.

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Chapter 7
Sediment Properties

Section I
General

7-1. Purpose

This chapter focuses on the properties of inorganic noncohesive sediments. Generally, organics do not significantly affect sedimentation processes. The percentage of organics in field samples should be determined and then the organics should be removed before testing for the inorganic sediment properties. If a significant quantity of organic particles are present, then a suitable procedure for correcting the calculations must be developed.

7-2. Property Categories

Sediment properties can be divided into two categories: (a) those related to the particle itself and (b) those related to the sediment mixture or deposit.

Section II
Particles

7-3. General

When the sediment particles are noncohesive, mechanical forces dominate the behavior of the sediment in water. Particle hydrodynamics refers to the propensity of a particle to remain immobile or to become entrained if it is on the bed surface, and to remain in suspension or to cease movement if it is in motion. The three most important properties that govern the hydrodynamics of noncohesive sediments are particle size, shape, and specific gravity. Cohesive sediment behavior is dominated by electrochemical forces. Cohesive sediment behavior is primarily dependent on the particle size, water chemistry, and sediment mineralogy.

7-4. Particle Size

Particle size is the most significant sediment property of noncohesive natural sediments. Frequently, the particle size alone is used to characterize a sediment particle. This procedure is acceptable if the particle shape and density are "typical" of natural sediments.

a. Particle size definitions. Particle size is defined by one of four methods:

(1) The ***nominal diameter*** of a particle is the diameter of a sphere that has the same volume as the particle.

(2) The ***sieve diameter*** of a particle is the length of the side of the smallest square opening through which the given particle will pass.

(3) The ***sedimentation diameter*** of a particle is the diameter of a sphere that has the same specific gravity and has the same terminal settling velocity as the given particle in the same fluid under the same conditions.

(4) The ***standard fall diameter*** (or simply ***fall diameter***) of a particle is the diameter of a sphere that has a specific gravity of 2.65 and has the same terminal settling velocity as the given particle in quiescent distilled water at a temperature of 24 °C.

b. Particle classification. Sediment particles are classified, based on their size, into six general categories: *Clay, Silt, Sand, Gravel, Cobbles,* and *Boulders*. Because such classifications are essentially arbitrary, many grading systems are to be found in the engineering and geologic literature. Table 7-1 shows a grade scale proposed by the subcommittee on Sediment Terminology of the American Geophysical Union (Lane 1947). This scale is adopted for sediment work because the sizes are arranged in a geometric series with a ratio of two. This classification is different from the Unified Soils Classification System commonly used in geotechnical work.

7-5. Particle Shape

Particle shape is the second most significant sediment property in natural sediments and can be defined by the shape factor, SF.

$$SF = \frac{c}{\sqrt{a\ b}} \tag{7-1}$$

where a, b, and c are the lengths of the longest axis, the intermediate axis, and the shortest axis, respectively. These axes are the mutually perpendicular axes of the particle. The shape factor for a sphere would be 1.0. Natural sediment typically has a shape factor of about 0.7. Particle shape affects the fall velocity and, hence, both the sedimentation diameter and fall diameter of particles. The relationship between sieve diameter and fall diameter as a function of shape for a specific gravity of 2.65 was determined by the Interagency Committee on Water Resources (1957) and is shown in Figure 7-1. *

*

Table 7-1
American Geophysical Union Sediment Classification System

	Sediment Size Range		
Sediment	millimeters	microns	Inches
Very large boulders	4096 - 2048		160-80
Large cobbles	256 - 128		80-40
Medium boulders	1024 - 512		40-20
Small boulders	512 - 256		20-10
Large cobbles	256-128		10-5
Small cobbles	128-64		5-2.5
Very coarse gravel	64-32		2.5-1.3
Coarse gravel	32 - 16		1.3-0.6
Medium gravel	16 - 8		0.6-0.3
Fine gravel	8 - 4		0.3-0.16
Very fine gravel	4 - 2		0.16-0.08
Very coarse sand	2.0 - 1.0	2000-1000	
Coarse sand	1.0 - 0.5	1000-500	
Medium sand	0.5 - 0.25	500-250	
Fine sand	0.25 - 0.125	250-125	
Very fine sand	0.125 - 0.062	125-62	
Coarse silt	0.062 - 0.031	62-31	
Medium silt	0.031 - 0.016	31-16	
Fine silt	0.016 - 0.008	16-8	
Very fine silt	0.008 - 0.004	8-4	
Coarse clay	0.004 - 0.002	4-2	
Medium clay	0.002 - 0.001	2-1	
Fine clay	0.0010 - 0.0005	1.0 - 0.5	
Very fine clay	0.0005 - 0.00024	0.5 - 0.24	

7-6. Particle Specific Gravity

In natural soils, particle specific gravity will usually

> "range numerically from 2.60 to 2.80. Within this range, the lower values for specific gravity are typical of the coarser soils, while higher values are typical of the fine-grained soil types. Values of the specific gravity outside the range of values given may occasionally be encountered in soils derived from parent materials which contained either unusually light or unusually heavy minerals." [Ritter and Paquette 1960, p 182]

Due to its resistance to weathering and abrasion, quartz, which has a specific gravity of 2.65, is the most common mineral found in natural noncohesive sediments. Typically, the average specific gravity of a sediment mixture is close to that of quartz. Therefore, in sedimentation studies, specific gravity is frequently assumed to be 2.65, although whenever possible, site-specific particle specific gravity should be determined.

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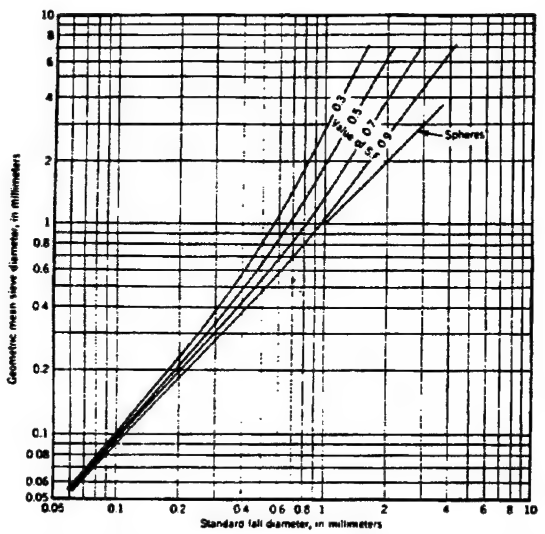

Figure 7-1. Relation of sieve diameter and fall diameter for naturally worn quartz particles (Interagency Committee 1957)

7-7. Particle Fall Velocity

Fall velocity is a general term describing the rate of fall or settling of a particle in a fluid. The standard fall velocity of a particle is the average rate of fall that the particle would finally attain if falling alone in quiescent distilled water of infinite extent and at a temperature of 24 °C. The fall diameter of a particle is the diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle. Fall velocity is the most fundamental property governing the motion of the sediment particle in a fluid; it is a function of the volume, shape, and density of the particle and the viscosity and density of the fluid. The fall velocity of any naturally worn sediment particle may be calculated if the characteristics of the particle and fluid are known. The relationship between sieve diameter and fall velocity of quartz particles in distilled water is shown in Figure 7-2. This figure shows the variation in this relationship with temperature and shape factor. These are average values, and fall velocities for individual particles may vary widely. Similar relationships can be developed for other shape factors and specific gravities using the method outlined by the Interagency Committee on Water Resources (1957). The Interagency Committee method has been computerized and is available as CORPS program H0910 (USAEWES - CORPS) and in the Hydraulic Design Package - SAM (Thomas et al. 1994).

7-8. Methods for Obtaining Particle Size

Particle sizes are determined using a variety of methods. Methodology is usually size-dependent. Diameters of particles larger than 256 mm may be obtained by measuring the intermediate or b-axis. Templates with square openings can be used to determine a size equivalent to the sieve diameter for particles between 32 and 256 mm.

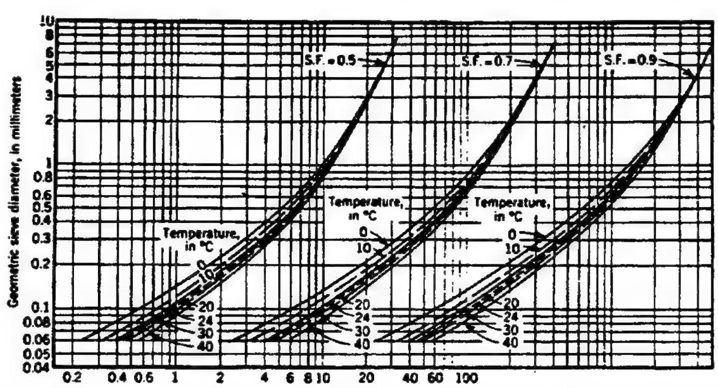

Figure 7-2. Relationship of sieve diameter and fall velocity for naturally worn quartz particles falling alone in quiescent distilled water of infinite extent (Interagency Committee 1957)

*

* Sieve analyses are typically used for particles between 0.0625 and 32 mm. A visual accumulation tube may be used to determine fall diameter for particles between 0.0625 and 2.0 mm. Hydraulic settling methods are used for particles less than 0.0625 mm in diameter. These include the pipet method, which is considered the most reliable indirect method; the bottom withdrawal method, which can be used if there is not enough material for a pipet method; and the hydrometer method, which is relatively simple and can be accomplished at a lessor cost, but which requires a larger sample quantity. These methods are discussed in detail in Chapter III of ***Sedimentation Engineering*** (ASCE 1975).

7-9. Cohesiveness

The cohesion of a sediment particle is associated with soil type and particle size. The three most common minerals which have electrochemical forces causing individual particles to stick together are illite, kaolinite, and montmorillonite. Sediment studies in the coastal zone and in reservoirs must evaluate the behavior of cohesive sediments. Methods are generally labeled as "cohesive sediment transport." The boundary between cohesive and noncohesive sediments is not clearly defined. It can be stated, however, that cohesion increases with decreasing particle size for the same type of material. Clays are much more cohesive than silts. Cohesive sediment is characterized by the dispersed particle fall velocity, flocculated fall velocity of the suspension, the clay and nonclay mineralogy, organic content, and the cation exchange capacity. The fluid is characterized by the concentration of important cations, anions, salt, pH, and temperature. More detailed information is presented in EM 1110-2-1607 (USAEHQ 1991).

Section III
Sediment Mixtures

7-10. Gradation Curves

The variation in particle sizes in a sediment mixture is described with a gradation curve, which is a cumulative size-frequency distribution curve showing particle size versus accumulated percent finer, by weight (Figure 7-3). It is common to refer to particle sizes according to their position on the gradation curve. For example: d_{50} is the geometric mean particle size; that is, 50 percent of the sample is finer, by weight; $d_{84.1}$ is 1 standard deviation larger than the geometric mean size--in practice it is rounded to d_{84}; and $d_{15.9}$ is 1 standard deviation smaller then the geometric mean size and is rounded to d_{16} in practice.

a. AGU Classification. The gradation curve shown in Figure 7-3 is a standard form used in the Corps of Engineers. The size class classification shown on the form is the Unified Soils Classification System, which is commonly used in geotechnical engineering studies. Whereas particle sizes versus percent finer are the same in sedimentation studies as they are in geotechnical studies, the size classification terminology is different. Always clarify by stating the AGU size classification is being used when reporting sedimentation investigations. Although a standardized form using the AGU size classification system is not available, one can be created on one of several computer graphics packages as shown in Figure 7-4.

b. Distribution. Natural river sediments are typically distributed log-normally. Hence, gradation curves are plotted on semi-logarithmic paper, and the geometric mean and geometric standard deviation are used to describe the distribution. The geometric mean size is calculated as:

$$d_g = \sqrt{d_{84}\, d_{16}} \tag{7-2}$$

The geometric standard deviation is calculated as:

$$\sigma_g = 0.5 \left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}} \right) \tag{7-3}$$

It is common practice to use these definitions for mean sediment size and standard deviation in a mixture even if the distribution is not log-normal.

Section IV
Sediment Deposits

7-11. General

Properties of sediment deposits are defined in terms of the deposit's porosity, specific weight, and consolidation rate.

7-12. Porosity

Porosity of deposited sediment is volume of voids divided by the total volume of sample.
*

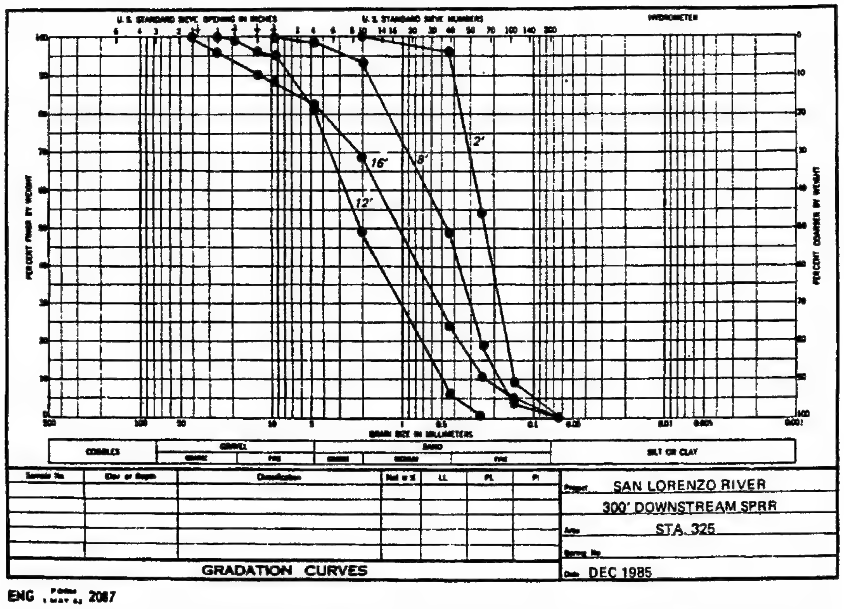

Figure 7-3. Gradation curve

$$P = \frac{V_v}{V_t} \tag{7-4}$$

where

P = porosity

V_v = void volume

V_t = total volume of sample

7-13. Specific Weight

Specific weight of a deposit is the weight per unit volume. It is expressed as dry weight.

$$\gamma_d = (1 - P)\, SG\, \gamma$$

$$or \tag{7-5}$$

$$\gamma_d = (1 - P)\, \gamma_s$$

where

γ_d = specific weight of deposit

SG = specific gravity of sediment particles

γ = specific weight of water (approximately 62.4 lb/ft^3)

γ_s = specific weight of sediment particles

Standard field tests are recommended when major decisions depend on the specific weight of the sediment deposit. When field data are not available for a project site, the tables on pages 39-40 of ***Sedimentation Engineering*** (ASCE 1975) may be used.

7-14. Consolidation

Consolidation is the process of compaction of a deposit with time or with overburden pressure.

$$\gamma_{dc} = \gamma_{di} + B \log_{10} T \tag{7-6}$$

where

γ_{dc} = consolidated weight of the deposit

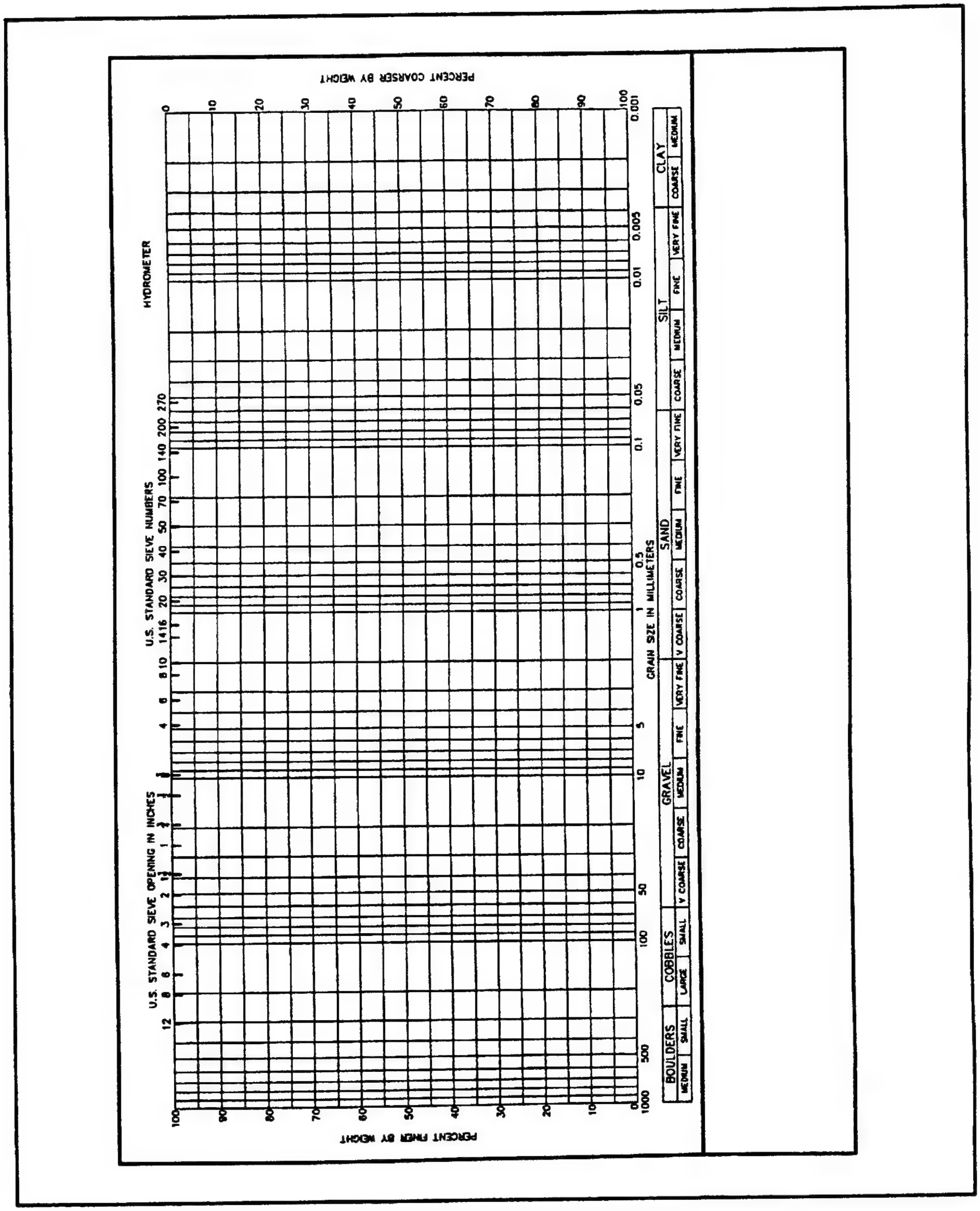

Figure 7-4. AGU gradation curve

*

* γ_{di} = specific weight of the initial deposit

B = coefficient of consolidation, which varies with size classification (suggested values can be found in ***Sedimentation Engineering*** (ASCE 1975) - p 43)

T = age of the deposit, years

When dealing with mixtures of particle sizes, calculate compaction for clay, silt, and sand fractions separately; then calculate the composite specific weight of the mixture using the following equation:

$$\gamma_d = \frac{1.0}{\left(\frac{F}{\gamma_d}\right)_{clay} + \left(\frac{F}{\gamma_d}\right)_{silt} + \left(\frac{F}{\gamma_d}\right)_{sand}} \tag{7-7}$$

where F is the fraction. Do not use the percent weighted specific weight in the γ_d terms of Equation 7-7. It does not conserve mass of the mixture.

Section V
Water-Sediment Mixtures

7-15. Sediment Concentration

Sediment concentration is the weight of dry sediment in a water-sediment mixture per volume of mixture and is expressed in milligrams/liter (mg/l). Sediment concentration sometimes is expressed in parts per million (ppm), which is the ratio of the mass of dry sediment in a water-sediment mixture to the mass of the mixture times 10^6. If the concentration is less than 16,000 mg/l, then concentration in part per million is essentially the same as milligrams/liter. For concentrations greater than 16,000 mg/l, milligrams/liter and parts per million are related by the following equations:

$$C_{ppm} = \frac{10^6}{SG_w\left(\frac{10^6}{C_{mgl}} + \frac{1.0}{SG_w} - \frac{1.0}{SG_s}\right)} \tag{7-8}$$

$$C_{mgl} = \frac{10^6}{\left(\frac{1.0}{SG_w}\frac{10^6}{C_{ppm}} - \frac{1.0}{SG_w} + \frac{1.0}{SG_s}\right)} \tag{7-9}$$

where

C_{ppm} = concentration, ppm

C_{mgl} = concentration, mg/l

SG_s = specific gravity of sediment particles

SG_w = specific gravity of water

7-16. Sediment Discharge

Sediment discharge is the quantity of sediment per unit of time passing a cross section. It is expressed as tons/day. The equation to convert from concentration to sediment discharge is

$$QS = kCQ \tag{7-10}$$

where

QS = sediment discharge, tons/day

k = 0.0027 when other variables are expressed in designated units

C = concentration, mg/l

Q = water discharge, cfs

Sometimes sediment discharge is expressed in units of cubic feet per second (cfs). Sediment discharge in tons per day can be converted to cubic feet per second using the following equation:

$$QS_{cfs} = 0.02315\frac{QS_{tons/day}}{\gamma_s} \tag{7-11}$$

where γ_s is the specific weight of the sediment in pounds per cubic feet (pcf).

7-17. Sediment Load

Sediment load denotes the material that is being transported, whereas sediment discharge denotes the rate of transport. Sediment load is described with a variety of terminology. Sediment load is generally defined based on *

* mode of transport, by its availability in the streambed, orby the method of measurement (Table 7-2). Based on the mode of transport, sediment load can be divided into bed load and suspended load. Bed load is the sediment load transported close to the bed where particles move intermittently by rolling, sliding, or jumping. Turbulence supports suspended load throughout the water column, and sediment is swept along at about the local flow velocity. Based on its availability in the streambed, sediment load can be divided into bed-material load and wash load. Wash load consists of the finest particles in the suspended load that are continuously maintained in suspension by the flow turbulence and, thus, significant quantities are not found in the bed. Particles that move as suspended load or bed load and periodically exchange with the bed are part of the bed-material load. This is the sediment load that can be calculated from the composition of the streambed. Based on measurement technique, sediment load is described as either measured or unmeasured. Typically, when depth-integrated suspended sediment samplers are used, the lower 0.5 ft of the water column is unmeasured. The unmeasured load includes some of the suspended and usually all of the bed load. Although the relative proportion of the total load indicated in Table 7-2 is typical of many streams, variation in these relative amounts does exist between sites and at different times at the same site.

Section VI
References for Chapter 7

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Table 7-2
Explanation of Total Load

Mode of Transport	Availability in Streambed	Method of Measurement
Suspended	Wash	Measured
	Bed Material	
Bed		Unmeasured

*

* U.S. Army Engineer Waterways Experiment Station (USAEWES). Conversationally Oriented Real-Time Program System (CORPS) Computer Programs. Available from ATTN: CEWES-IM-MI-C, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. *

* # Chapter 8
# Sediment Measurement Techniques

Section I
Sediment Measurement Equipment

8-1. General

Satisfactory resolution of problems associated with sediment transported in streams requires both an understanding of sedimentation processes and a knowledge base of physical data. Between 1925 and 1940, in order to gather data for an increasing number of sediment studies, investigators developed new sediment samplers to measure fluvial sediment. However, developmental efforts were independent from one another, and most of the samplers were placed into service without calibration. As a result, a reliable database was not being obtained because the data were not comparable nor could their accuracy be evaluated. In 1939, the United States Government organized an Interagency program to study methods and equipment used in measuring sediment discharge and to improve and standardize equipment and methods. This organization is known as the Federal Interagency Sedimentation Project (FISP).

8-2. Federal Interagency Sedimentation Project

FISP was initially located at the Institute of Hydraulic Research at the University of Iowa. In 1948, it was moved to the St. Anthony Falls Hydraulic Laboratory, at the University of Minnesota. In 1992, it was relocated to the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. The Corps of Engineers has always been a major contributor to FISP and has benefitted greatly both from the use of the standardized equipment and procedures developed by the project, and from the reliable database generated by other agencies. Each Federal agency that provides financial support to FISP has one member on a technical subcommittee which guides the work of the project.

8-3. Characteristics of Ideal Sediment Sampler

The requirements of an ideal time-integrating suspended sediment sampler were summarized by Nelson and Benedict (1951).

a. The velocity at the entrance of the intake tube should be equal to the local stream velocity.

b. The intake should be pointed into the approaching flow and should protrude upstream from the zone of disturbance caused by the presence of the sampler.

c. The sample container should be removable and suitable for transportation to the laboratory without loss or spoilage of the contents.

Furthermore, the sampler should

d. Fill smoothly without sudden inrush or gulping.

e. Permit sampling close to the streambed.

f. Be streamlined and of sufficient weight to avoid excessive downstream drift.

g. Be rugged and simply constructed to minimize the need for repairs in the field.

h. Be as inexpensive as possible, and consistent with good design and performance.

The 35 samplers developed and used prior to 1940 were tested by FISP, and the results indicated that none met the criteria stated above.

8-4. Standardized Equipment

The US-series of suspended-sediment samplers developed by FISP embody most of the required and desirable features for an ideal sampler. All US-series integrating samplers provided by FISP are designed and calibrated to sample isokinetically. That is, the water-sediment mixture moves with no acceleration from the ambient flow into the sampler's nozzle intake. This ioskinetic property is critical to obtaining an accurate representation of sediment concentration. The samplers developed by FISP are designated based on their function and the year designed. For example, with a US DH-75 sampler, D signifies depth integrating, H signifies hand held, and 75 indicates the sampler was designed in 1975. A US P-61 is a point (P) integrating sampler designed in 1961. Except in unique circumstances, when specialized equipment is required, standardized equipment, provided and calibrated by FISP, should be used for data collection for Corps of Engineers projects. Inquiries regarding performance specifications and purchase of these samplers should be addressed to the Federal Inter-Agency Sedimentation Project, CEWES-HR-RF, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199. *

* 8-5. Depth-Integrating Samplers

Depth-integrating samplers are designed to accumulate a water-sediment sample as the instrument is lowered to the streambed and raised to the surface at a uniform rate. The nozzle, either 1/8, 3/16, 1/4, or 5/16 in. in diameter, is always open. Use of the 1/8-in. nozzle is discouraged because it tends to plug easily and surface roughness in the bore may affect the sampling rate. This nozzle is generally used only when conditions do not permit use of larger nozzles. Particle sizes which can be collected range from clays through sands. The sampling depth is limited to about 15 ft or less depending on the size of the nozzle.

a. Hand-held. Where streams can be waded or where a low bridge is available, lightweight hand-held samplers can be used to obtain depth-integrated suspended-sediment samples. The US DH-48 is a streamlined aluminum sampler, which weighs 4.5 lb, collects samples in a pint bottle, and can sample to within 3.5 in. of the bed. The US DH-59 and US DH-76 are bronze cast samplers, collect samples in pint and quart size bottles, respectively, and were designed to be suspended from a hand-held rope in streams too deep to wade. The US DH-59 and US DH-76 weigh about 22 and 25 lb, respectively; applicability is limited to cases where the velocity is less than 5 fps. These lightweight hand-held samplers are the most commonly used for sediment sampling during normal flow in small and intermediate sized streams. The US DH-75 was designed for use in subfreezing winter conditions. It is lightweight and therefore can be thawed easily with a small torch. The US DH-75 sampler may be used with a pint or a quart plastic bottle and most of the working parts are made of plastic.

b. Cable and reel. When streams cannot be waded, but are less than 15 ft deep, a US D-74 depth-integrating sampler can be used. The US D-74 is a 62-lb bronze cast sampler and is used with a cable and reel suspension. Samples are collected in a pint or quart bottle and the US D-74 can sample to within 4 in. of the streambed. Maximum calibrated velocity for the US D-74 is 6.6 fps. The US D-77 was designed to collect large-volume (3 ℓ) depth-integrated samples. This sampler is used extensively in water-quality sampling because all components that contact the sample are made of plastic or Teflon. The US D-77 weighs 75 lb and samples to within 7 in. of the bottom. Maximum calibrated velocity is 8 fps.

8-6. Point-Integrating Samplers

Point-integrating samplers are more versatile than the simpler depth-integrating types. They can be used to collect a sample at any selected point in the water column, or they can be used to sample continuously over a range of up to 30 ft in depth. This limit results from the requirement to maintain ambient pressure in the sample bottle as the sample is collected. Because of their greater mass, point-integrating samplers can be used in streams too deep or swift for the standard depth-integrating samplers. Point-integrating samplers contain an air compression chamber which allows for pressure equalization in the sample bottle up to depths of 180 ft when a pint-sized sample bottle is used. With a quart-sized bottle, depths up to 120 ft can be sampled. Sampling is controlled by a rotary valve, which is operated electrically by the operator. By positioning the sampler at the streambed before opening the valve, and sampling while transiting upward to the surface, a depth-integrated sample can be collected through a 30-ft deep water column. In deeper streams, a depth-integrated sample can be collected by partitioning the total depth into segments, up to about 30 ft each, and by using a constant transit velocity throughout. The US P-61, which weighs 105 lb, is the classical point-integrating sampler. The distance between the nozzle and the sampler bottom is 4.3 in. A lightweight version of the US P-61 is the aluminum cast US P-72, which weighs about 41 lb. For swifter streams, the 200-lb US P-63 can be used. The US P-63 can sample to within 5.9 in. of the streambed. The US P-50, weighing 300 lb, is a special point-integrating sampler developed for and used on large rivers such as the lower Mississippi.

8-7. Auxiliary or Automatic Sampling Equipment

Single-stage samplers were developed as an aid in obtaining information on flashy streams. The most severe limitation of single-stage samplers is that they collect samples of the water-sediment mixture at a fixed point in the steam and, therefore, are most effective in streams carrying predominately fine sediments. The single-stage sampler may be a static sampler such as the US U-59, which consists of a pint bottle filled from a vertical or horizontal intake tube using siphonic action or it may utilize a pump. In case of the pump, the velocity in the intake is not usually equal to the stream velocity, and the intake does not usually point into the flow. Whereas, silt and clay *

* sizes collected in such samplers may be representative, pumping samplers generally significantly underestimate the concentration of sand sizes in the flow field (Hall and Fagerburg 1991) as shown in Figure 8-1. Sediment samples collected from automatic sampling equipment must be calibrated to samples collected from cross-section depth-integrated or point-integrated samples for reliable results.

8-8. Bed Samplers

a. FISP samplers. Bed samplers designed by FISP are limited to collecting samples where the maximum grain size is less than fine gravel. The samplers are also limited to relatively firm beds; i.e. they are not designed to collect samples from unconsolidated deposits of silt or clay. The US BMH-53 is a hand-held piston-type sampler for sampling the bed of wadable streams. The collecting end of the sampler is a stainless steel thin-walled cylinder 2 in. in diameter and 8 in. long. Sediments composed primarily of sands are difficult to sample with the US BMH-53 because the material tends to fall from the barrel when the cutting edge is lifted above the streambed. For noncohesive materials, in wadable streams, the US RBM-80 sampler is available. It is a manually operated lever-and-cable system with a rotating bucket that collects a sample along a 51-mm arc. The bucket closure is sufficiently sealed to prevent loss of the sample while the instrument is lifted through the water column. The bed of deeper streams or lakes can be sampled with the US BMH-60. This is a hand-line streamlined sampler with a spring-driven rotary bucket. It weighs 32 lb and is easiest to use in any reasonable depth when stream velocities are under 3 fps. The rotary bucket penetrates the bed to about 1.7 in. and holds about 175 cc of sample. The US BM-54 is a cable and reel suspension sampler with a design similar to the US BMH-60, but weighing 100 lb. The extra weight allows for sampling at any reasonable depth and in swifter streams.

b. Nonstandard bed samplers. Nonstandardized bed samplers are frequently used for special applications,

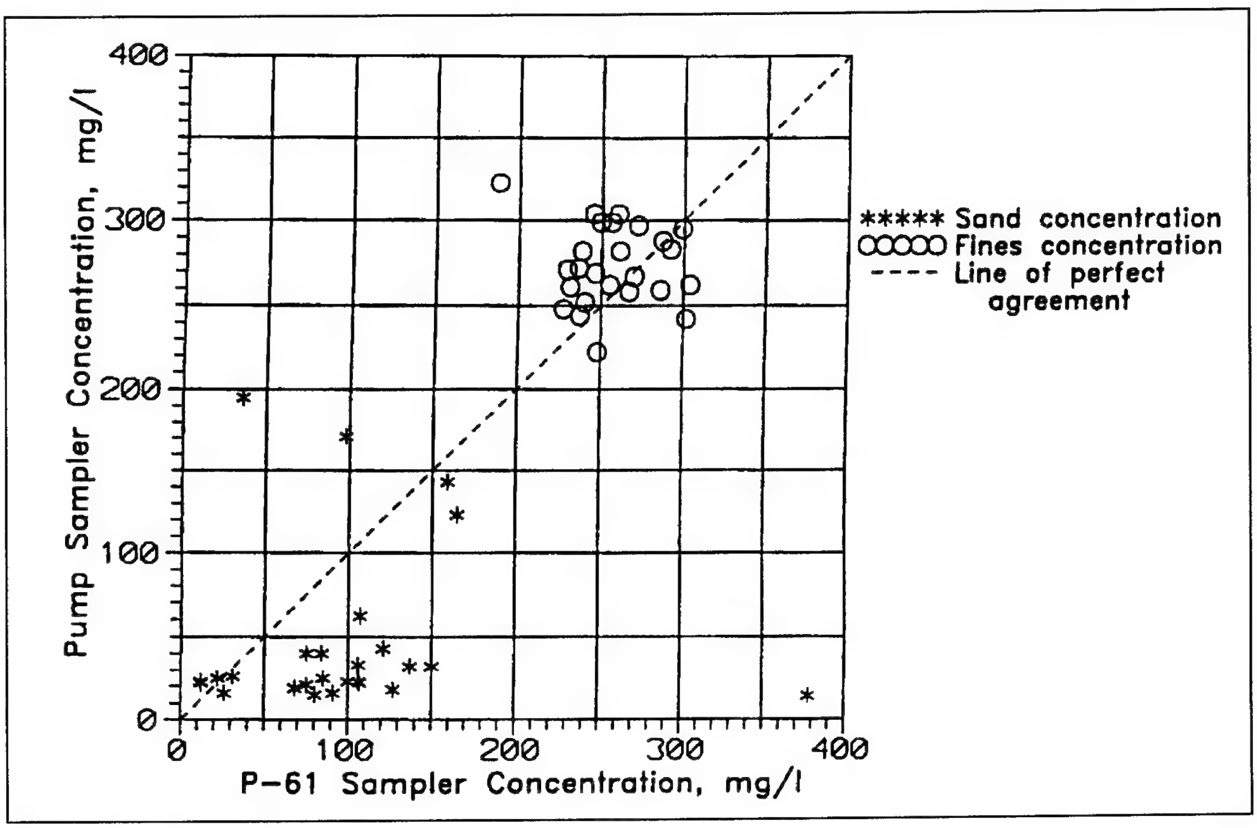

Figure 8-1. Comparison of sediment load measured with pump and US P-61 samplers

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* or when the standardized equipment is deemed unnecessary. Drag bucket, pipe samplers, and scoop samplers simply collect a sample into an open container by dragging or scooping. The disadvantage with these sampler types is that material, especially fine material, may be washed out of the container as the sample is brought to the surface. Clamshell samplers can be used when stream velocity is low. These have the disadvantage of frequent nonclosure if gravel is present in the sample, and they create a significant disturbance on the bed of streams with moderate to high velocity.

c. Gravel-bed samplers. Samplers for obtaining short cores in shallow water in gravel- or cobble-bed streams are described in ASTM Standard D-4823 (ASTM, published annually). These include a barrel sampler, with a serrated cutting edge, that is driven into the bed. Once the sampler is in place, sediment is excavated, by hand, layer-by-layer. Another sampler is a freeze-core sampler. This device is a hollow probe that is driven into the streambed and cooled with liquid nitrogen. The device is then extracted with a frozen core of sediment adhered to it.

d. Core samplers. When the purpose of the sampling program is to obtain information on the vertical composition of deposits to determine density and compaction, then an undisturbed sample is required. These samples are collected using core samplers or piston-core samplers that have removable sample-container liners. Fine sediments are generally cored easily, but in sand and gravel deposits it is difficult to obtain deep cores. Coring deep into sediment generally requires drilling equipment or special pile-driving equipment, which may produce samples that are highly disturbed or compacted. Several deep-core samplers are described in ASTM Standard D-4823 (published annually), and ***Sedimentation Engineering*** (ASCE 1975, pp 357-369.)

e. Acoustical techniques. Recent advances in geoacoustics have resulted in the development of geophysical methods to assess the characteristics of bottom and subbottom sediments. Specifically, the engineering properties of sediments (i.e. density, mean grain size, soil classification, etc.) have been empirically related to the measured acoustic impedance of different sediment types. Acoustic impedance, z, is the product of the mass density, ρ, and elastic compressional wave sound velocity, v, ($z = \rho\ v$) through a sediment layer and, thus, represents the influence of the medium's characteristics on reflected and transmitted acoustic waves. McGee et al. (1995) present a detailed discussion of the application of acoustical techniques for the assessment of in situ sediment properties.

8-9. Bed-Load Samplers

Bed load is difficult to measure for several reasons. Any mechanical device placed on the bed disturbs the flow and hence the rate of bed-load movement. In addition, bed load is characterized by extensive spatial and temporal variability. For this reason, the sampling technique is just as important as the sampling equipment. The Helly-Smith bed-load sampler is the most commonly used sampler in the United States. FISP recommends a bed-load sampler with a nozzle flare angle that is different from that on the Helly-Smith sampler. In general, the overall sampling efficiency of a specific sampler is not constant, but varies with size distributions, stream velocities near the bed, turbulence, rate of bed-load transport, and the degree of filling of the sampler.

Section II
Standard Sampling Procedures

8-10. General

Detailed procedures used by the U.S. Geological Survey for measurement of fluvial sediments are contained in a report by Edwards and Glysson (1988) (which may be obtained from the Distribution Branch, U.S. Geological Survey, 604 So. Pickett Street, Alexandria, VA 22304) and in ASTM Standard D-4411 (published annually). A brief summary of these procedures is outlined herein.

8-11. Depth Integration

The procedure for collecting depth-integrated samples is to lower the sampler to the water surface, so that the nozzle is out of the water and the tail vane is in the water until the sampler is properly aligned with the flow. Depth integration is achieved by lowering the sampler to the streambed at a uniform transit rate and then immediately raising the sampler at a uniform rate until the nozzle clears the water surface. Each transit must be at a uniform rate, but the raising and lowering transits may be at different rates. In order to minimize the effect of nonhorizontal flow entering the nozzle, transit rates should not exceed four-tenths of the mean velocity. Other factors may limit the transit rate to significantly lower values. Transit depths are limited by the rate of air compression in the sample bottle. In addition, transit rates should be such that at the end of sampling, the sample *

* bottle is about two-thirds full. If the bottle is overfilled, i.e. filled to within 1.5 in. of the top, the sample should be discarded. Graphs for determining transit rates as a function of nozzle diameter, mean velocity, and depth of integration are provided in Edwards and Glysson (1988, pp 69-72). When the stream is shallow, or the velocity is low, several transits may be made to obtain the appropriate sample volume and several sample verticals may be included in a single sample bottle.

a. Single vertical. Streams with a stable cross section and insignificant lateral variation in the suspended-sediment load may be sampled using a single vertical. The same vertical is usually used for all discharges. The best location for the single vertical is determined by trial when the station is established. Detailed sediment-discharge measurements employing several verticals across the entire width of the stream at a range of discharges must be conducted at a new gaging site in order to determine the location for the single vertical sampling point. The vertical should be located at least 10 ft from any supporting pier. The results of the fixed vertical should be compared with frequent cross-sectional sampling in order to verify an adjustment factor for the total sediment concentration. This adjustment factor should especially be checked after major flood flows that alter the channel shape.

b. Multiple verticals. Lateral variation in depth, velocity, roughness, and grain size may make it unrealistic to relate sediment concentration for the entire cross section to concentration at a single vertical. A realistic sampling program may require sampling at two to five or more verticals. Verticals may be located by one of two methods: the method of the centroids-of-equal-discharge increments (EDI) across the stream, where the channel cross-sectional area is divided laterally into a series of subsections, each of which conveys the same water discharge; or the method of equally spaced verticals across the stream and an equal-width-increment (EWI) at all verticals (sometimes referred to as equal-transit-rate: ETR). The EDI method is usually limited to streams with stable channels where discharge ratings change very little during a year. The EWI method is most often used in shallow and/or sand-bed streams where lateral flow distribution is unstable. On the order of 20 verticals are usually ample for the EWI method. A nomograph to determine the number of sampling verticals required to obtain results within an acceptable relative standard error based on the percentage of sand in the sample, the average velocity, and the depth is given in Edwards and Glysson (1988, p 68). The EDI method requires some knowledge of the streamflow distribution before the sampling verticals can be selected, but this method can save time and labor over the EWI method, especially on larger streams because fewer verticals are required. Samples collected using the EDI method may be composited to obtain total concentration if sample bottles contain equal, or nearly equal, quantities of sample. Samples collected using the EWI method can be composited regardless of the volume in each sample.

c. Point integration. Point-integrating samplers are used in streams where depth exceeds the recommended 15 ft for a depth-integrating sampler and where the combination of depth and velocity cause the sample bottle to overfill at the maximum allowable transit rate. Also, in high velocities, the lighter depth-integrating samplers are unstable and the more massive point-integrating samplers should be used. Both the EWI and EDI methods are applicable to point-integrating samplers when they are used for depth integration. Stream depth increments up to 30 ft can be measured with point-integrating samplers by integrating the depth in only one direction. When depth integration is used in only one direction, at least two samples should be taken and composited at each vertical: one by downward integration and one by upward integration. Point-integrating samplers are sometimes used to obtain sample concentrations at several points or levels in the vertical from which the distribution of sediment concentration in the vertical can be computed. This method is slower and more labor-intensive than depth integration and should be reserved for special studies.

8-12. Bed-Load Sampling

Bed load moves sporadically as a series of pulses and also varies laterally across the stream. Due to the significant temporal and spatial variation in bed-load transport, many repetitive measurements must be made at a number of different lateral locations. Initially, 10 to 20 sampling verticals should be used. The sampling sequence must be long enough to include the passage of several bed forms to account for the temporal variation in transport rate. Consideration must be given to the variation in hydraulic forces through a reach that may cause certain size classes to move primarily as bed load in one reach, but as suspended load in another reach. This extensive sampling needs to be made over the entire range of stream discharges in order to obtain a reliable bed-load transport rating curve. The suggested technique for bed-load sampling is to sample at 20 verticals initially to define the active bed-load transport zone, then sample at 10 or more verticals *

* within that zone on subsequent transects. At least four transects should be taken. If it is apparent that temporal variations are more significant than spatial variations, then a smaller number of verticals may be sampled (about five), but many replications at each vertical should be conducted.

8-13. Bed Sampling

a. General. Deposited sediment is sampled to provide information on such things as size, specific gravity, shape, and mineralogy of the particles that make up the bed; stratigraphy, density, and compaction of the deposits; and the quantity and distribution of contaminants. For some of these purposes a sample can be disturbed; others require undisturbed sampling. Different samplers and sampling procedures are available for different environments.

b. For sediment transport studies. Typically, streambed samples are obtained in order to determine the potential for sediment transport. For this purpose, undisturbed samples are not required. The sample is taken from the upper 2 in. of the bed surface in sand-bed streams. In gravel-bed streams, samples of the armor layer and the subsurface layers should be collected. The sample depth for the armor layer should be about equal to the diameter of the maximum size class in the bed. The depth and quantity of sample for the subsurface depends on the size of sediment and the equipment being used. When sampling for sediment transport studies, do not sample over long distances along the stream. Collect all samples along cross sections to characterize that reach. Then proceed to the next sampling cross section and repeat the procedure.

c. Samples from dry beds. Sampling in the dry is preferred because there is less opportunity for fine-size classes to be lost from the sample during collection. Samples from dry beds are typically collected with a shovel or scoop. If there is an obvious layer of fine material on the surface of a dry bed, this should be removed before the sample is taken.

d. Samples from streams with flowing water. In order to obtain satisfactory samples in flowing water, the bed sampler should enclose a volume of the bed material and then isolate the sample from the water currents while the sampler is being lifted to the surface. The sampler should disturb the flow field as little as possible while taking a sample. These criteria are met with standardized FISP US BM-54 and US BMH-60 samplers. Under certain flow conditions, simple drag bucket and pipe samplers have been shown to produce bed gradations similar to those obtained with the US BM-54. A comparison with standardized samplers should be conducted for each case. Open-ended drag bucket and pipe samplers are typically used from a boat. One technique is to lower the sampler to the bed and allow the boat to drift with the current. The sample is dredged up as the boat moves downstream. As the boat continues to drift, the sampler is hoisted back to the surface.

e. Streams with coarse surface layers. Streams with coarse surface layers present a particular problem. For numerical studies of nonequilibrium flow conditions, the sample should include the coarse surface layer so that all of the particle sizes available for armoring are included in the sample. This practice requires that the coarse surface layer comprises only a small fraction (less than 5 percent) of the total sample. It is frequently necessary to obtain separate gradations of both the coarse surface layer and the subsurface layer.

f. Lateral variations. Lateral variation in the bed gradation is significant, especially in sand-and-gravel bed streams and at channel bends. At least three samples should be taken across the cross section to account for lateral variations. In streams with variable depths more samples are required. Taking bed samples at crossings where flow distribution is typically more uniform, reduces the lateral variation in the samples. However, at low flow, crossings may become coarser than the average gradation and should not be selected as a sampling location for sediment transport studies. This is especially true of steep streams that develop riffle and pool planforms. Samples collected on point bars or alternate bars may exhibit considerable variation. Figure 8-2 illustrates a typical bed gradation pattern on a point bar. Note that, although the typical grain sizes found on the bar surface form a pattern from coarse to fine, there is no one location which always captures the precise distribution which will represent the entire range of processes in the prototype. There is no simple rule for locating sampling sites. The general rule is "always seek representative samples." That is -- ***carefully select sampling locations and avoid anomalies which would bias either the calculated sediment discharge or the calculated bed stability against erosion.*** A good practice is to take samples at a crossing and at a point or alternate bar just above the low water level to establish a range of uncertainty for the bed gradation. Dead water areas behind sandbars or bridges should be avoided. *

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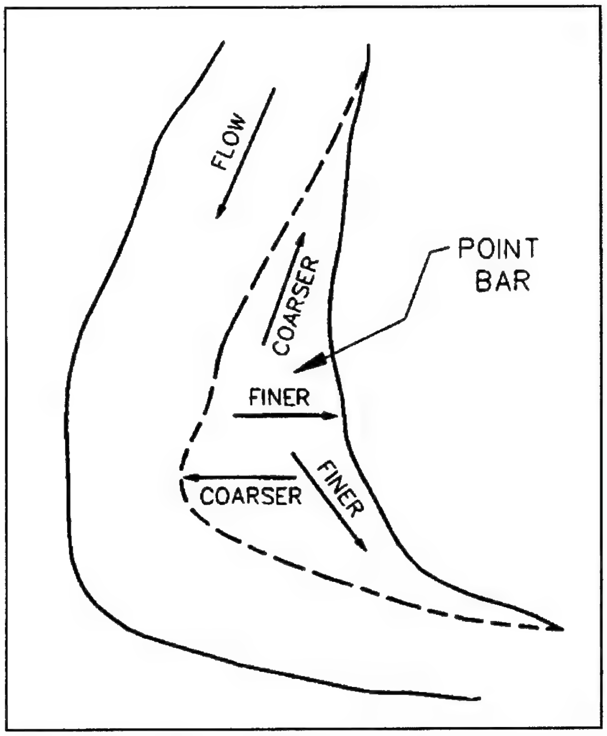

Figure 8-2. Gradation pattern on a bar

g. Coarse beds. When bed particle size is too large to obtain a manageable quantity of sample for sieve analysis, a pebble count (Wolman 1954) may be conducted where individual particles are collected at random by hand and the intermediate (b) axis is measured. This method requires that the stream be wadable. At least 100 particles should be included in the sample. One method for choosing the particles is a random walk laterally across the stream or longitudinally along a point bar, another is to set up a grid and measure particles at the intersection of grid points. The gradation curve developed from these data is based on the number of particles in each size class, not their weights.

8-14. Suspended-Sediment Sampling in Lakes, Reservoirs, and Estuaries.

Sediment measurement in low-velocity environments requires different equipment and techniques than in streams. As flow velocity approaches zero, movement, if any, results from complex circulation patterns, density currents, or tidal flow. Cross-sectional areas are usually very large; and instantaneous water discharges are rarely known. Sampling techniques need to be evaluated for accuracy and pertinence to the objective of the sampling program. Most samplers used in low-velocity environments are point or trap samplers that are oriented vertically and do not sample isokinetically. Frequently, samples are collected using pumping samplers. Due to continuous changes in sediment concentration in estuaries, neither the EDI or EWI methods for sampling are appropriate. General practice is to sample continuously through a tidal cycle at a number of locations to define temporal variation at each location. Field procedures for lake and reservoir sampling are found in ***Sedimentation Engineering*** (ASCE 1975, pp 369-375.) Procedures for estuarine sampling are found in EM 1110-2-1607.

Section III
Laboratory Analysis

8-15. Suspended-Sediment Concentration

Evaporation and filtration are the two most frequently used methods for determining sediment concentration. The filtration method is faster if the quantity of sediment in the sample is small and/or relatively coarse grained. In addition, if the quantity of sediment is small, the evaporation method requires a correction if the dissolved-solids concentration is high. The evaporation method is usually best for high concentrations of sediment (>2,000 mg/l), such as those encountered in many arid-region streams. Laboratory procedures for both methods are well documented (ASCE 1975, pp 404-406; Guy 1969; U.S. Interagency Report 1941).

8-16. Particle-Size Analysis

Sediment particles vary not only in size, but in shape and specific gravity. Particles of a given size will behave as if they were larger or smaller depending on how their shape and specific gravity compare with standard values. Due to the wide range in sediment characteristics, particle size should be defined in terms of the method of analysis used to determine the size. Methods for determining sediment gradations are grouped into fine-sediment methods and coarse-sediment methods. The most commonly used methods for determining the gradation of fine sediment are the hydrometer, the bottom withdrawal tube, and the pipet. The X-ray method is a new method for determining fine sediment gradation. Two generally accepted methods for determining the size-distribution of sand are the sieve and visual-accumulation tube methods. The sieve method measures physical diameter, whereas all other methods measure sedimentation diameter. A given

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* sediment sample may require more than one method of analysis because of the broad range of particle sizes. Recommended quantities of sediment sample, the desirable range in concentration, and the recommended particle size range for the most frequently used methods of particle-size analysis are shown in Table 8-1. Additional guidance for selection of a particle-size analysis is given in ASTM Standard D-4822 (published annually).

Many suspended-sediment samples will not contain sufficient sediment for any of these methods, in which case, the analysis may be limited to simply determining the percentage of sands and fines. A greater quantity of sediment may be obtained by using larger bottles in samplers or by compositing samples. Sometimes samples require splitting to obtain a reasonable quantity for analysis.

a. Hydrometer method. Laboratory procedures for conduction of the hydrometer method are contained in *EM 1110-2-1906.* This method has been used extensively in the study of soils. Although the method is relatively simple and inexpensive, its use in sediment work has been limited to fine-grained bed and bank material because of the need for a relatively large quantity of sediment.

b. Bottom withdrawal method. The bottom-withdrawal method requires specially constructed and calibrated tubes. It is not used extensively. This method is more accurate for very low concentrations of fine materials than the pipet method; however, it is more time consuming. The bottom withdrawal method is described in ***Sedimentation Engineering*** (ASCE 1975, pp 418-424)

c. Pipet method. The pipet method is the most routinely used method for fine sediment (clay and silt) analysis. The sample initially is dispersed uniformly throughout the pipet apparatus. Concentrations of the quiescent suspension are determined at predetermined depths and times based on Stokes law. The primary disadvantage with this method is its high labor intensity. The pipet method in described in ***Sedimentation Engineering*** (ASCE 1975, pp 416-418), and Guy 1969).

d. X-ray methods. The U.S. Geological Survey has recently approved usage of X-ray grain-size analyzers to determine fall diameter for clay and silt mixtures. The sample is dispersed uniformly in the instrument which measures decreasing concentration with time. Cumulative mass percentage distributions are determined automatically. X-ray analysis requires less time than the pipet method and is therefore less expensive. Comparisons of pipet and X-ray methods have shown that X-ray methods tend to produce slightly finer gradations. When the X-ray method is employed, duplicate samples on at least 10 percent of the samples at a site should be taken until a relationship between the X-ray and pipet results can be established.

e. Sieve method. Sieve analysis is a relatively simple method for obtaining a gradation for sediment larger than 0.0625 mm. Unfortunately, U.S. standard sieves do not correlate exactly with the AGU size class classification system. A set of U.S. standard sieves range between 3 in. and 0.074 mm. As discussed in Chapter 7 sediment diameters determined from sieve analysis do not necessarily correspond to equivalent spherical diameters. Sieve analysis does not account for variations in particle shape or specific gravity. Procedures for application of sieve analyses are found in *EM 1110-2-1906.* The required sample size is a function of the maximum particle size. A guide for obtaining a minimum-weight sample is given in Table 8-2.

Table 8-1
Recommended Quantities for Particle-Size Analysis

Method	Size Range, mm	Analysis Concentration, mg/l	Quantity of Sediment, grams
Sieve	0.062 - 64		0.07 - 64,000
VA tube	0.062 - 2.0		0.05 - 15.0
Pipet	0.002 - 0.062	2,000 - 5,000	1.0 - 5.0
BW tube	0.002 - 0.062	1,000 - 3,000	0.5 - 1.8
Hydrometer	0.002 - 0.062	40,000	30.0 - 50.0

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Table 8-2
Sample Size for Sieve Analysis

Maximum Particle Size, in.	Minimum Weight of Sample grams	pounds
3.0	64,000	140
2.0	19,000	42
1.5	8,000	18
1.0	2,400	5.3
0.75	1,000	2.2
0.5	300	0.66
0.375	150	0.33
0.187	50	0.11
Particle Size Range, mm		
16.0 - 1.0	20	0.044
2.0 - 0.25	0.5	0.0011
0.5 - 0.062	0.07	0.00015

Note: For streams with maximum sizes larger than 3 in., the required sample weight should be at least 100 times the weight of the maximum size.

f. Visual accumulation method. The visual accumulation (VA) method is used to determine the fall diameter of sands. Sediment finer than 0.062 mm is removed from the sample and analyzed by either the pipet or bottom withdrawal methods. Particles larger than 2 mm must be removed and measured by sieve analysis. In the VA method, sediment is added at the top of a settling tube and the deposited sediment is stratified according to the settling velocities of the various particles in the mixture. A continuous trace of the deposited sediment at the bottom of the VA tube is produced by the analysis. The VA apparatus may be obtained from the FISP which also supplies an operator's manual.

Section IV
Developing a Sediment Discharge Rating Curve

8-17. Preparation from Measured Data

Success in developing sediment-discharge rating curves will depend on the foresight in establishing an adequate sediment measuring program prior to the need for data. Sediment-discharge rating curves are prepared from measured data, sometimes available in annual USGS Water Resource Publications for each state. Calculated mean daily sediment discharges are frequently published; these are calculated values and should not be used to develop a sediment-discharge rating curve. An example data set is shown in Figure 8-3. Note that fall diameters are reported in columns 7-14 and sieve diameters in columns 15-20. Sieve analyses were apparently conducted for samples with low sediment concentrations, where there were insufficient quantities available for VA analyses. For most of these samples, only a fines/sand break was determined.

a. Separation by sediment load type. Sediment-discharge rating curves should be prepared for the total measured load and the measured bed-material load. The sediment-discharge rating curve for the total measured suspended load can be developed from data in columns 3 and 6 in Figure 8-3 (although a much larger data set is required for a reliable rating curve). Total suspended sediment load alone is not sufficient to analyze the sediment discharge characteristics. It is also important to separate the wash load from the bed-material load because their transport is governed by different relationships: wash load is dependent on upstream supply, and bed-material load is dependent on the availability of the sediment in the streambed. The size-class break between wash load and bed-material load is frequently assumed to correspond to the break between sand and silt (0.0625 mm); however, this assumption is not always valid. Bed gradations at the gage site are required in order to distinguish the wash load from the

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
DATE	TIME	STREAM-FLOW, INSTAN-TANEOUS (CFS) (00061)	TEMPER-ATURE (DEG C) (00010)	SEDI-MENT, SUS-PENDED (MG/L) (80154)	SEDI-MENT, DIS-CHARGE, SUS-PENDED (T/DAY) (80155)	SED. SUSP. FALL DIAM. % FINER THAN .002 MM (70337)	SED. SUSP. FALL DIAM. % FINER THAN .004 MM (70338)	SED. SUSP. FALL DIAM. % FINER THAN .016 MM (70340)	SED. SUSP. FALL DIAM. % FINER THAN .062 MM (70342)	SED. SUSP. FALL DIAM. % FINER THAN .125 MM (70343)	SED. SUSP. FALL DIAM. % FINER THAN .250 MM (70344)	SED. SUSP. FALL DIAM. % FINER THAN .500 MM (70345)	SED. SUSP. FALL DIAM. % FINER THAN 1.00 MM (70346)	SED. SUSP. SIEVE DIAM. % FINER THAN .062 MM (70331)	SED. SUSP. SIEVE DIAM. % FINER THAN .125 MM (70332)	SED. SUSP. SIEVE DIAM. % FINER THAN .250 MM (70333)	SED. SUSP. SIEVE DIAM. % FINER THAN .500 MM (70334)	SED. SUSP. SIEVE DIAM. % FINER THAN 1.00 MM (70335)	SED. SUSP. SIEVE DIAM. % FINER THAN 2.00 MM (70336)
NOV																			
01...	1000	577	7.5	152	237	--	--	--	--	--	--	--	--	57	72	84	95	100	--
08...	1415	799	12.5	223	481	--	--	--	--	--	--	--	--	40	51	75	98	100	--
29...	1145	940	9.0	578	1470	--	--	--	--	--	--	--	--	17	25	43	77	98	100
JAN																			
03...	1000	512	.0	277	383	--	--	--	--	--	--	--	--	19	31	62	93	97	100
FEB																			
01...	1230	791	6.0	38	81	--	--	--	--	--	--	--	--	72	81	96	99	100	--
28...	0900	1390	7.0	324	1220	--	--	--	47	55	82	100	--	--	--	--	--	--	--
APR																			
02...	0900	1460	8.0	411	1620	--	--	--	--	--	--	--	--	60	--	--	--	--	--
28...	1300	6440	12.0	2410	41900	7	8	11	28	45	70	96	100	--	--	--	--	--	--
MAY																			
02...	1200	4970	12.5	943	12700	--	--	--	36	59	84	98	100	--	--	--	--	--	--
JUN																			
01...	1200	5460	13.0	326	7720	--	--	--	43	57	73	97	100	--	--	--	--	--	--
13...	1600	6900	15.0	1490	27800	--	--	--	--	--	--	--	--	15	--	--	--	--	--
JUL																			
11...	1000	3550	22.0	299	2870	--	--	--	32	46	79	100	--	--	--	--	--	--	--
29...	0900	722	17.0	606	1180	--	--	--	--	--	--	--	--	96	--	--	--	--	--
AUG																			
15...	1015	304	23.5	234	192	--	--	--	--	--	--	--	--	93	95	98	100	--	--
SEP																			
12...	1430	409	26.0	273	301	--	--	--	--	--	--	--	--	94	95	99	100	--	--

Figure 8-3. Measured sediment-discharge data

*

* bed-material load. The bed gradation should account for lateral variations across the cross section using an appropriate averaging technique. Einstein (1950) recommended using only the coarsest 90 percent of the sampled bed gradation for computations of bed-material load. He reasoned that the finest 10 percent of sediment on the bed was either trapped material or a lag deposit and should not be included in bed-material load computations. Once the division between wash load and bed-material load is determined, the percent finer data from the appropriate column in Figure 8-3 can be used with the total concentration in column 5 and the discharge in column 3 to calculate wash load. If sufficient data are available, separate sediment-discharge rating curves should be developed for each size class in the bed-material load. For studies involving inflow to reservoirs, separate sediment-discharge rating curves should be developed for each size class in the wash load too. In order to accomplish this type of analysis it is necessary that adequate numbers of particle-size analyses are conducted on the collected sediment concentrations. Unfortunately, particle-size data are frequently insufficient to develop sediment-discharge rating curves as described in the preceding paragraph. In such cases, a minimum requirement is to develop separate curves for the fines (clays and silts) and the sands.

b. Approximations by calculation. When measured data are insufficient to develop a sediment-discharge rating curve for each size class, then sediment transport equations must be employed to develop rating curves for individual size classes. The percentage of each size class in the suspended load will vary with discharge (the percentage of fines will be greater at lower discharges). Therefore, it is inappropriate to develop sediment-discharge rating curves for mixed size-classes using the average of measured size-class fractions.

c. Adjustment for unmeasured load. Sediment-discharge rating curves developed from measured suspended-sediment data need to be adjusted to account for the unmeasured load. This can be accomplished using the Modified Einstein Equation (ASCE 1975, pp 214-220), if the hydraulic parameters, concentration data by particle size, and bed-material gradations are available. A computer program for computing the unmeasured load with the Modified Einstein Equation is available on the CORPS system (USAEWES). If data are not available, the unmeasured load may be assumed to be a percentage of the measured load equal to the percentage that the bed load is of the total load. Bed-load percentage for a stream can be determined using the Einstein or Toffaleti sediment transport equation. These are computerized in the CORPS system (USAEWES) and in SAM (Thomas, et al. 1995.)

d. Bed load. Developing sediment-discharge rating curves from measured bed-load data is more difficult. Bed load moves in pulses and varies laterally across the stream. Therefore, significantly more measurements are necessary to obtain a reliable average condition. It has been demonstrated in gravel-bed streams and flumes that the percentage of each size class in the bed load closely corresponds to its percentage in the subsurface layer (Andrews and Parker 1987; Kuhnle 1989; and Wilcox and McArdell 1993). If a given gravel-bed stream is in equilibrium, it is not unreasonable to assume that the percentage of each size class in the bed load equals the percentage in the bed substrate.

8-18. Scatter of Data Points

At most sediment gage sites a relatively good correlation between flow discharge and sediment discharge can be developed. However, sediment discharge depends on other variables as well, such as upstream supply, water temperature, roughness, and downstream stage. Therefore, data scatter is expected in sediment-discharge rating curves. At some gages, separate curves need to be developed for the rising and falling limbs of flood hydrographs and /or for different seasons on the year.

a. Wash load. Wash load is determined by its supply from upstream sources and is relatively independent of flow discharge, although flow discharge may be a good surrogate parameter because greater runoff from the watershed and greater bank erosion usually accompany higher flow discharge. Wash load is almost always greater on the rising limb of a flood hydrograph when finer sediment stored in the system is re-suspended, as shown in Figure 8-4. Typically, considerable scatter occurs about the average sediment-discharge curve for wash load.

b. Bed-material load. Bed-material load is very dependent on the hydraulic variables, which in turn are closely related to flow discharge; therefore, less scatter about the average sediment-discharge curve is expected. This is another reason to develop separate sediment-discharge curves for wash load and bed-material load.

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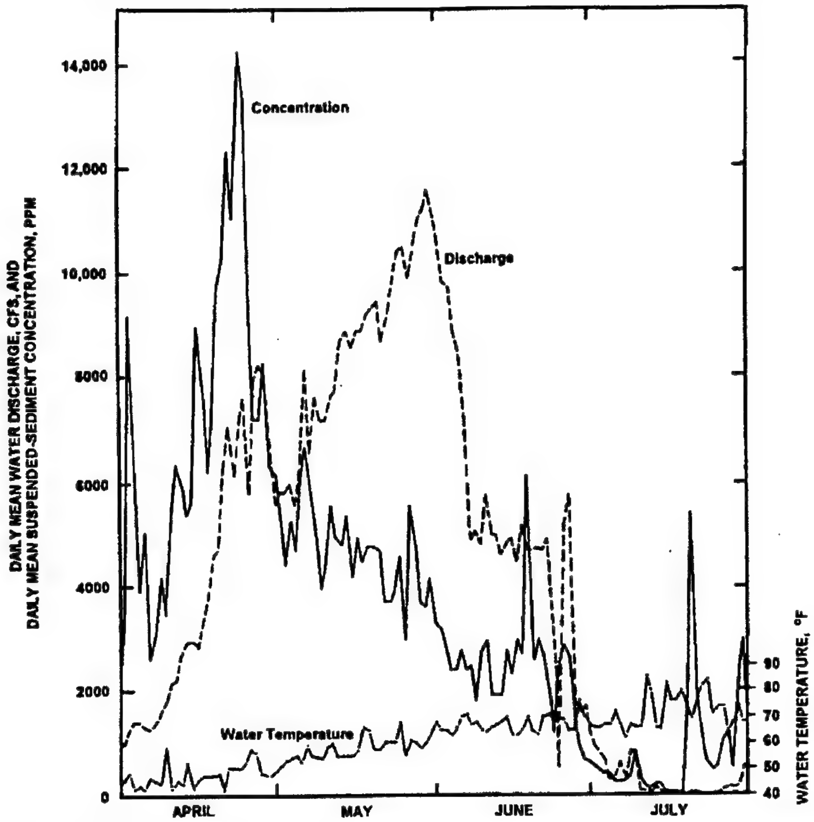

Figure 8-4. Mean daily water discharge and mean suspended-sediment concentration (Nordin and Beverage 1965)

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8-19. Predicting Future Conditions

The sediment-discharge rating curve may vary with time. This can be due to changes in land use or land management methods, construction of upstream reservoirs that trap sediment, construction of channel stabilization works that decrease bank erosion, or channel improvement work that increases channel conveyance and thus sediment transport potential. A significant downward trend in the average annual sediment discharge of the Mississippi River at Tarbert Landing in Mississippi is shown as an example in Figure 8-5. Although difficult to predict, the possibility of changes in the sediment-discharge rating curve over the project life should be considered.

8-20. Extrapolation to Extreme Events

Sediment data are seldom available for extreme events. This is due both to the infrequency of occurrence and the difficulty in obtaining sediment samples at high flows. Therefore, it is usually necessary to extrapolate the sediment-discharge rating curve developed from measured data. Typically, the rate of increase in sediment discharge with water discharge will decrease with an increase in the water discharge, especially for the finer size classes. The decline in rate of increase is more obvious when sediment concentration is plotted against discharge as shown in Figure 8-6. The decline in rate of increase occurs in the sand sizes as well, as shown in Figure 8-7. A more reliable extrapolation of the measured data for extreme events can be made if the extrapolation is based only on the high flow measured data. In the absence of measured data at high discharges, extrapolation of the sediment-discharge rating curve can be accomplished by calculating a sediment-discharge rating curve for each size class in the bed-material load and using the shape of the calculated curve to approximate the shape of the extrapolated curve.
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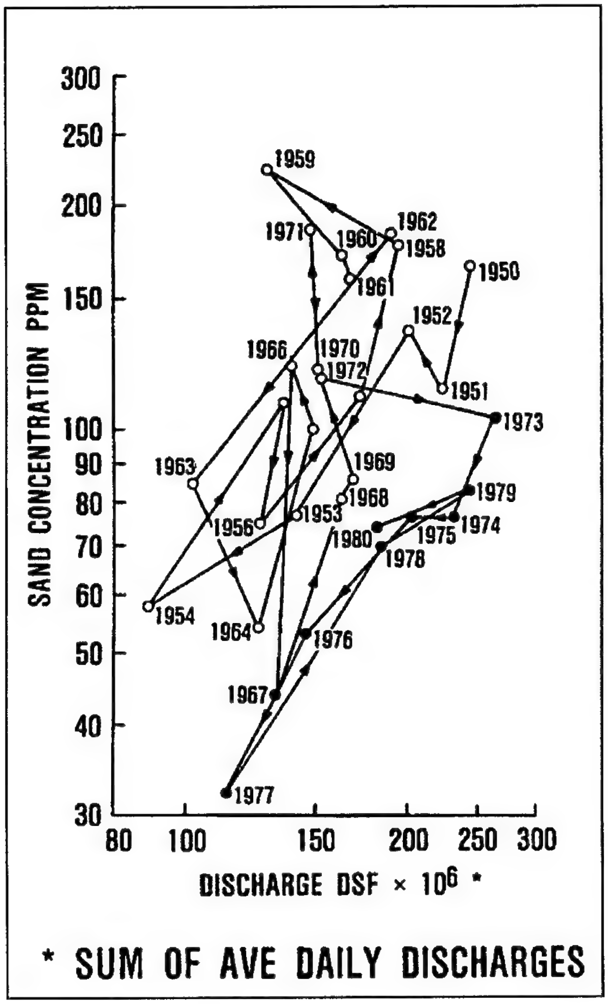

Figure 8-5. Average annual sediment concentration

Expect a high degree of uncertainty for any given grain size that comprises less than 10 percent of the bed.

Section V
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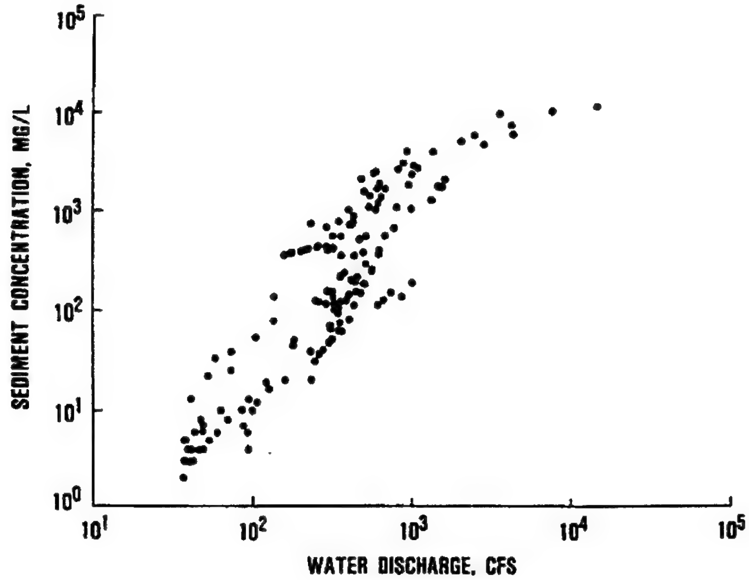

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Figure 8-6. Average daily sediment concentration

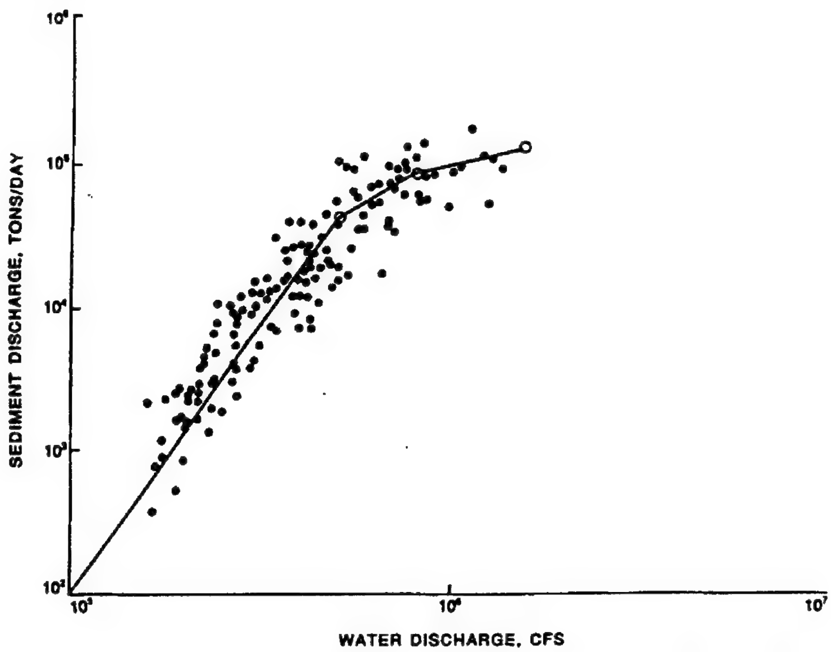

Figure 8-7. Very-fine sand sediment transport

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* # Chapter 9
# Sediment Transport Mechanics

Section I
Introduction

9-1. Definition

Sedimentation embodies the processes of erosion, entrainment, transportation, deposition, and compaction of sediment. These are natural processes that have been active throughout geological times and have shaped the present landscape of our world. The principal external dynamic agents of sedimentation are water, wind, gravity, and ice. Although each may be important locally, only hydrodynamic forces are considered herein. Transport functions, as typified by Einstein (1950), treat only the "transportation" process.

9-2. Topics Beyond the Material Presented in This Chapter

a. Local scour/deposition. Local scour, as compared to general erosion/deposition, refers to the scour hole that forms around a bridge pier or downstream from a hydraulic structure or along the outside of a bend, etc. It involves fluid forces from multidimensional flow accelerations, pressure fluctuations, and gravity forces on the sediment particles. The complexity of local scour processes relegates analysis to empirical equations or physical model studies. This chapter does not address local scour.

b. Cohesive sedimentation theory. The concept of the equilibrium condition does not apply to cohesive sediment transport as it does to noncohesive sediment transport. That is, in noncohesive sediment transport, there is a continual exchange of sediment particles between the water column and the bed surface. The equilibrium condition exists when the same number of a given type and size of particles are deposited on the bed as are entrained from it. That exchange process does not exist in cohesive sediment movement. Particle inertia due to its mass is insignificant in cohesive sedimentation problems in rivers. The dominant forces preventing cohesive particles from being eroded are electrochemical forces. That is, when cohesive particles come in contact with the bed, they are likely to adhere to it and resist re-entrainment. Deposition rates depend on flocculation of cohesive particles in suspension. There are analytical techniques for calculating the erosion, entrainment, transportation, deposition, and consolidation of cohesive sediments. However, it is a basic requirement to develop site-specific sediment properties from testing samples. Two fundamental properties are: (1) the shear stress for the initiation of erosion and deposition, and (2) the erosion rate. The erosion/deposition shear stresses are called erosion and deposition thresholds. Erosion rate is expressed as a function of bed shear stress. These relationships are needed for the full range of hydraulic conditions expected at the site. Finally, settling velocities are needed.

Section II
Initiation of Motion

9-3. General

Thresholds for particle erosion can be calculated, using average values for hydraulic parameters, if the fluid and sediment properties are known. The significant fluid properties are specific weight and viscosity. Significant sediment properties are particle size, shape, specific gravity, and position in the matrix of surrounding particles. In the case of cohesive particles the electrochemical bonds, related primarily to mineralogy, are the most significant sediment properties. Significant hydraulic forces are bed shear stress, lift, pressure fluctuations related to turbulence, and impact from other particles.

9-4. Shields Parameter

Although velocity has been used historically for predicting whether or not a particle will erode, Shields relationship between dimensionless shear stress (or Shields parameter), τ_*, and grain Reynolds number, R_*, is now recognized as a more reliable predictor. Shields parameter and grain Reynolds number are dimensionless, so that any consistent units of measurement may be used in their calculation. Although the experimental work and analysis were performed by Shields, the curve termed the Shields Curve, which is shown in Figure 9-1, was actually proposed by Rouse (ASCE 1975). Shields curve may be expressed as an equation, which is useful for computer programming.

$$\tau* = 0.22\ \beta + 0.06 \times 10^{-7.7\beta} \tag{9-1}$$

$$\beta = \left(\frac{1}{\nu} \sqrt{\left(\frac{\gamma_s - \gamma}{\gamma}\right) g d^3} \right)^{-0.6} \tag{9-2}$$

*

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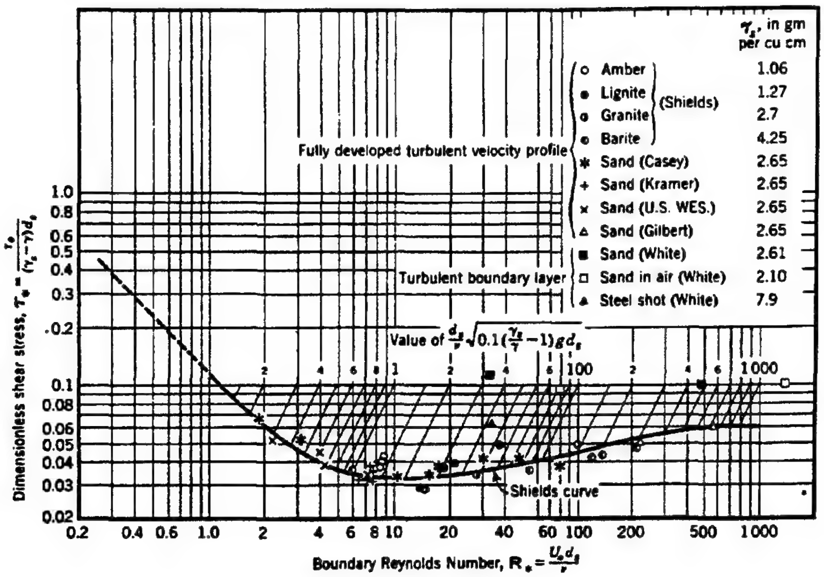

Figure 9-1. Shields curve (ASCE 1975)

where

τ_o = bed shear stress

γ_s = particle specific weight

γ = fluid specific weight

ν = kinematic viscosity of the fluid

g = acceleration of gravity

d = particle diameter

u_* = shear velocity = $(gRS)^{0.5}$

R = hydraulic radius

S = slope

The critical shear stress, τ_c, for stability of a particle having a diameter, d is then calculated from the following equation:

$$\tau_c = \tau_* (\gamma_s - \gamma) d \qquad (9\text{-}3)$$

9-5. Adjusted Shields Parameter

Shields obtained his critical values for τ_* experimentally, using uniform bed material, and measuring sediment transport at decreasing levels of bed shear stress and then extrapolating to zero transport. There are three problems associated with the critical dimensionless shear stress as determined by Shields. First, the procedure did not account for the bed forms that developed with sediment transport. A portion of the total shear is required to overcome the bed form roughness; therefore the calculated dimensionless shear stress was too high. Gessler (1971) reanalyzed Shields' data so that the critical Shields parameter represented only the grain shear stress which determines sediment transport and entrainment (Figure 9-2). Secondly, the critical dimensionless shear stress is based on the average sediment transport of numerous particles and does not account for the sporadic entrainment of individual particles at very low shear stresses. This becomes very important when transport of gravels and cobbles is of interest in low energy environments, and in the design of armor protection. This phenomenon was demonstrated by Paintal (1971) and is shown in Figure 9-3. Note that the extrapolated critical dimensionless shear
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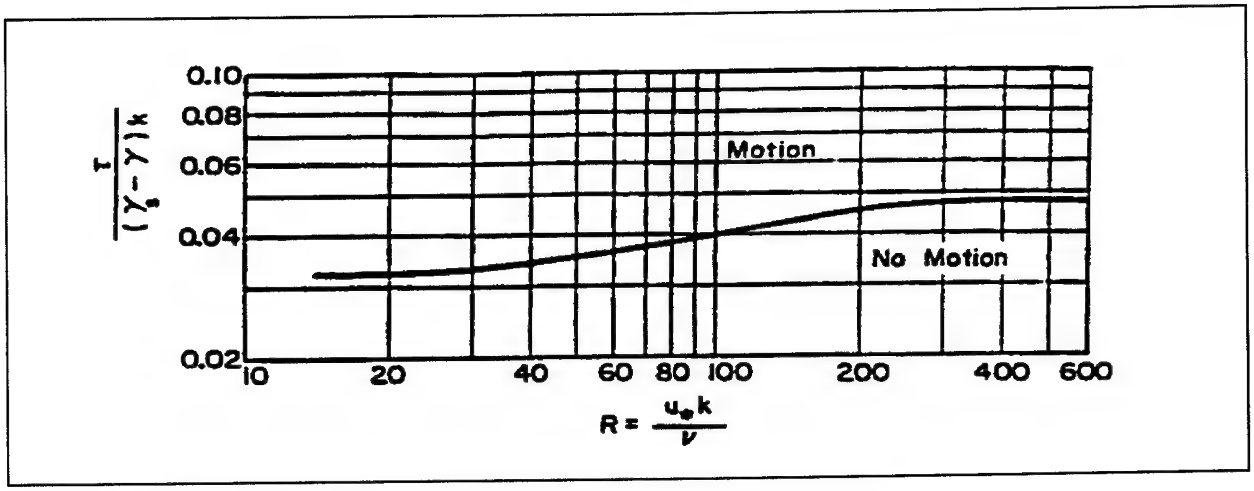

Figure 9-2. Shields diagram (Gessler 1971)

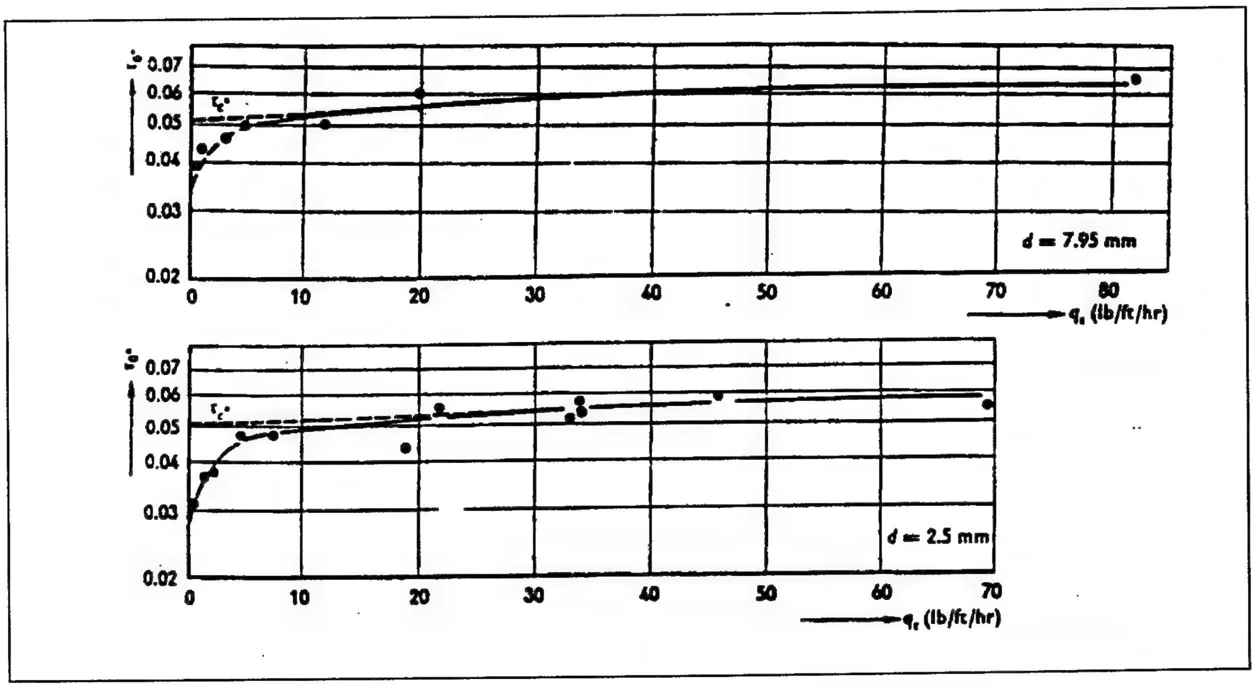

Figure 9-3. Determination of critical shear stress (Paintal 1971)

stress was about 0.05, but the actual critical dimensionless shear stress was 0.03. Thirdly, critical dimensionless shear stress for particles in a sediment mixture may be different from that for the same size particle in a uniform bed material. Meyer-Peter and Muller (1948) and Gessler (1971) determined from their data sets that the critical Shields parameter for sediment mixtures was about 0.047. Neill (1968) determined, from his data, that in gravel mixtures, most of the particles become mobile when τ_* for the median grain size was 0.030. Andrews (1983) found a slight difference in τ_*, for different grain sizes in a mixture, and presented the following equation:

*

*

$$\tau *_i = 0.0834 \left(\frac{d_i}{d_{50}} \right)^{-0.872} \tag{9-4}$$

where the subscript, i, indicates the Shields parameter value for size class i, and d_{50} is the median diameter of the subsurface material. The minimum value for τ_{*i} was found to be 0.020. According to Andrews, the critical shear stress for individual particles has a very small range; therefore, the entire bed becomes mobilized at nearly the same shear stress.

9-6. Gessler's Concept for Particle Stability

a. Critical shear stress is difficult to define because at low shear stresses entrainment is sporadic, caused by bursts of turbulence. It is even more difficult to define for particles in a coarse surface layer because the critical shear stress of one size class is affected by the presences of other size classes. Gessler (1971) developed a probabilistic approach to the initiation of motion for sediment mixtures. He reasoned that due to the random orientation of grains on the bed and the random strength of turbulence on the bed, for a given set of hydraulic conditions, part of the grains of a given size will move while others of the same size may remain in place. Gessler assumed that the critical Shields parameter represents an average condition, where about half the grains of a uniform material remain stable and half move. It follows then that when the critical shear stress was equal to the bed shear stress there was a 50 percent chance for a given particle to move. Using experimental flume data, he developed a probability function, **p**, dependent on τ_c/τ where τ_c varied with bed size class (Figure 9-4). He determined that the probability function had a normal distribution and that the standard deviation (slope of the probability curve) was a function primarily of turbulence intensity and equal to 0.057. Gessler found the effect of grain-size orientation to be negligible. The standard deviation also accounts for hiding effects, i.e. no attempt was made to separate hiding from the overall process. Gessler's analysis demonstrates that there can be entrainment of particles even when the applied shear stress is less than the critical shear stress, and that not all the particles of a given size class on the bed will necessarily be entrained until the applied shear stress exceeds the critical shear stress by a factor of 2.

b. Gessler suggested that the mean value of the probabilities for the bed surface to stay should be a good indicator of stability:

$$\bar{P} = \frac{\int_{i_{min}}^{i_{max}} P^2 f_i \, di}{\int_{i_{min}}^{i_{max}} P \, f_i \, di} \tag{9-5}$$

Where $\bar{p}$ is the probability function for the mixture and depends on the frequency of all grain sizes in the underlying material, and f_i is the fraction of grain size i. Gessler suggested that when $\bar{p} > 0.65$ that the surface layer of the bed would be unstable.

9-7. Grain Shear Stress

a. The total bed shear stress may be divided into that acting on the grains and that acting on the bed forms. Entrainment and sediment transport are a function only of the grain shear stress. Grain shear stress thus must be determined in order to make sediment transport calculations. Einstein (1950) determined that the grain shear stress could best be determined by separating total bed shear stress into a grain component and a form component which are additive. The equation for total bed shear stress is:

$$\tau_o = \tau' + \tau'' = \gamma RS \tag{9-6}$$

where

τ_o = total bed shear stress

τ' = grain shear stress

τ'' = form shear stress

b. Einstein (1950) also suggested that the hydraulic radius could be divided into grain and form components that are additive. The equations for grain and form shear stress then become

$$\begin{aligned} \tau' &= \gamma R' S \\ \tau'' &= \gamma R'' S \end{aligned} \tag{9-7}$$

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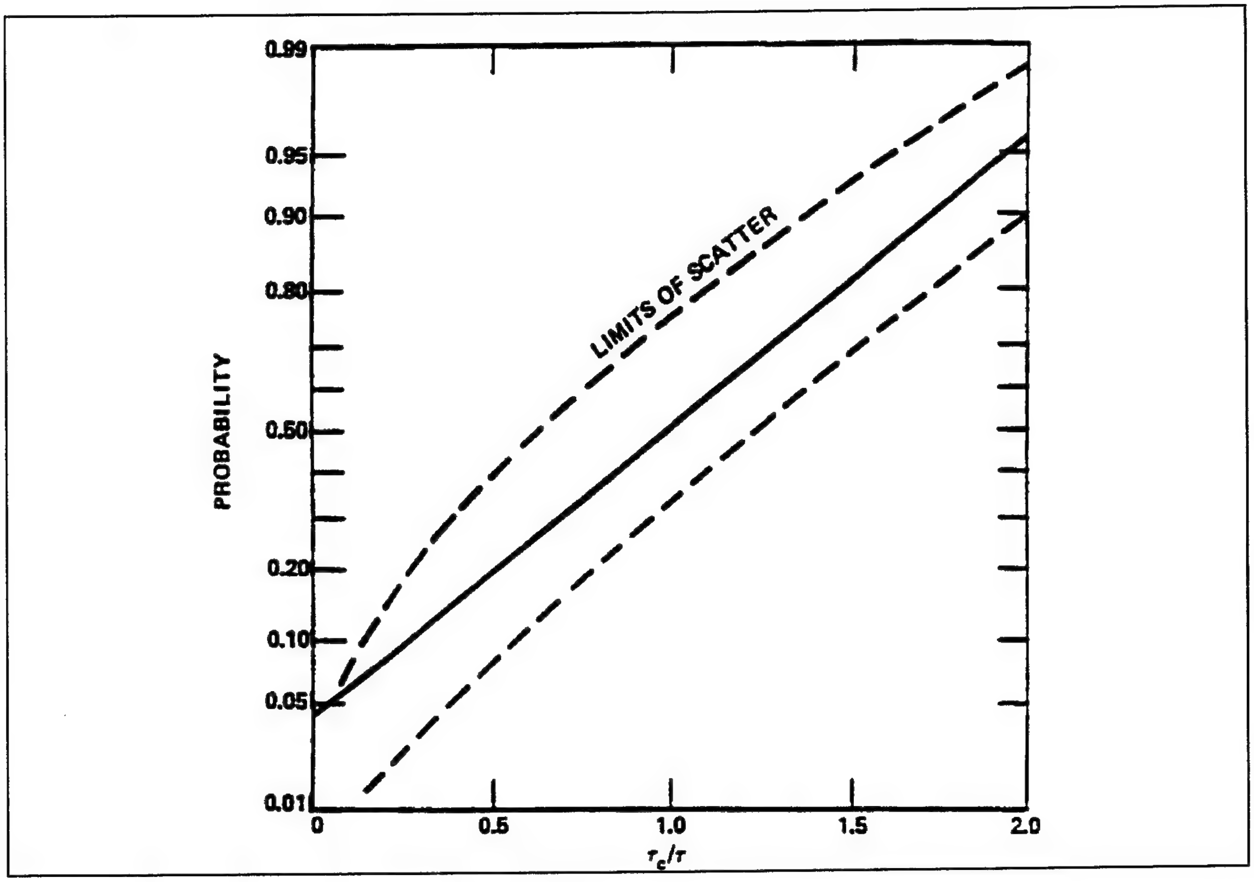

Figure 9-4. Probability of grains to stay (Gessler 1971)

where R' and R'' are hydraulic radii associated with the grain and form roughness, respectively. The total bed shear stress can be expressed as

$$\tau_o = \gamma R' S + \gamma R'' S \tag{9-8}$$

Slope and the specific weight of water are constant, so that the solution becomes one of solving for one of the R components. The Limerinos (1970) equation can be used to calculate the grain roughness component.

$$\frac{V}{U*'} = 3.28 + 5.66 Log_{10} \frac{R'}{d_{84}} \qquad U*' = \sqrt{gR'S} \tag{9-9}$$

where V is the average velocity and d_{84} is the particle size for which 84 percent of the sediment mixture is finer. Limerinos developed his equation using data from gravel-bed streams. Limerinos' hydraulics radii ranged between 1 and 6 ft; d_{84} ranged between 1.5 and 250 mm. This equation was confirmed for sand-bed streams without bed forms by Burkham and Dawdy (1976). The equation can be solved iteratively when average velocity, slope, and d_{84} are known.

9-8. Bed-Form Shear Stress

Einstein and Barbarossa (1952) used data from several sand-bed streams to develop an empirical relationship between bed form shear velocity and a dimensionlesssediment mobility parameter, Ψ'. The relationship is shown in Figure 9-5.

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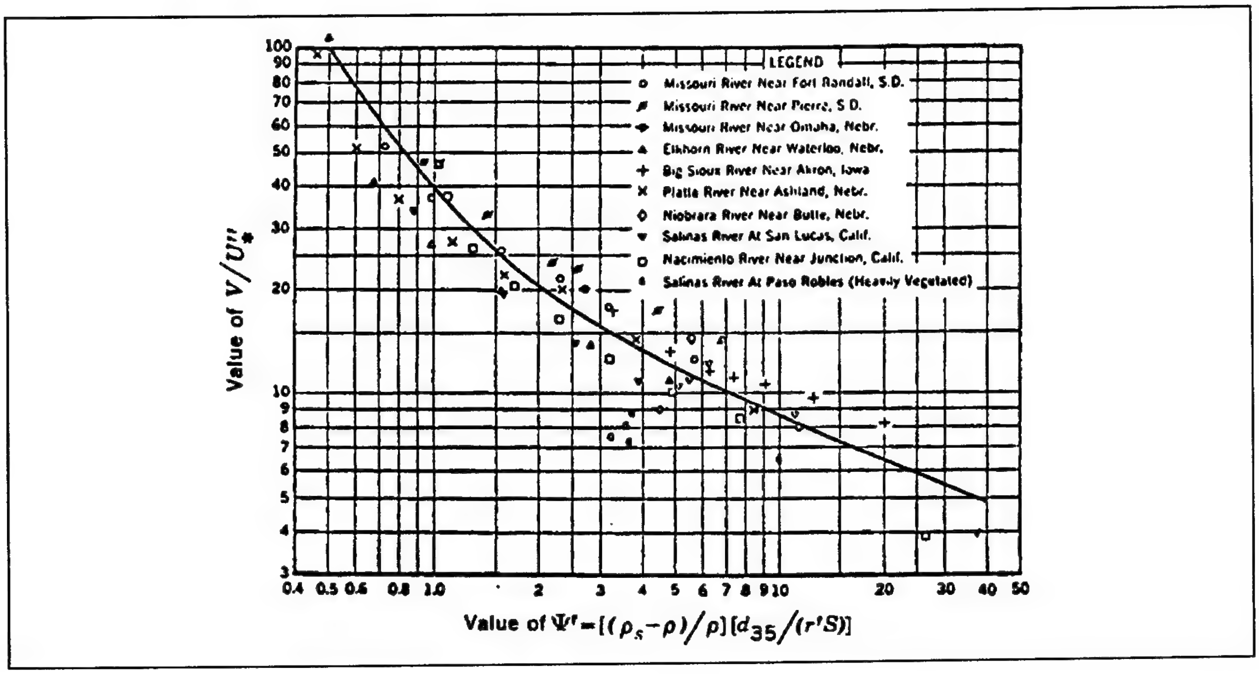

Figure 9-5. Bar resistance curve (Einstein and Barbarossa 1952)

$$\Psi' = \left(\frac{\gamma_s - \gamma}{\gamma}\right)\frac{d_{35}}{R'S} \tag{9-10}$$

where d_{35} is the particle size for which 35 percent of the sediment mixture is finer. R'' can be solved for directly using the following equation:

$$R'' = \frac{(U''_*)^2}{g\,S} \tag{9-11}$$

Typically, either the grain or form hydraulic radius is calculated directly, and the other hydraulic radius component is determined to be the difference between the total hydraulic radius and the calculated component.

9-9. Bank or Wall Shear Stress

Whenever the streambanks contribute significantly to the total roughness of the stream, the shear stress contributing to sediment transport must be further reduced. This is accomplished using the side-wall correction procedure which separates total roughness into bed and bank roughness and conceptually divides the cross-sectional area into additive components. The procedure is based on the assumption that the average velocity and energy gradient are the same in all segments of the cross section.

$$\begin{aligned} A_{total} &= A_b + A_w \\ A_{total} &= P_b R_b + P_w R_w \end{aligned} \tag{9-12}$$

where A is cross-sectional area, P is perimeter, and subscripts b and w are associated with the bed and wall (or banks), respectively. Note that the hydraulic radius is not additive with this formulation as it was with R' and R''. Using the Manning equation, with a known average velocity, slope, and roughness coefficient, the hydraulic radius associated with the banks can be calculated:

$$\frac{V}{1.486\,S^{1/2}} = \frac{R^{2/3}}{n} = \frac{R_w^{2/3}}{n_w} \tag{9-13}$$

$$R_w = \left(n_w \frac{V}{1.486\,S^{1/2}}\right)^{3/2} \tag{9-14}$$

where velocity is in feet per second and R is in feet. The side-wall correction procedure is outlined using the

* Darcy-Weisbach equation in ***Sedimentation Engineering*** (ASCE 1975, pp 152-154). Total hydraulic radius and shear stress considering grain, form, and bank roughness can be expressed by the following:

$$R_{total} = \frac{P_b(R' + R'') + P_w R_w}{P_{total}} \tag{9-15}$$

$$\tau_{total} = \gamma S \left(\frac{P_b(R' + R'') + P_w R_w}{P_{total}} \right) \tag{9-16}$$

Section III
Stage-Discharge Predictors

9-10. General

There are several stage-discharge predictors that have been developed for alluvial channels and these are presented in ***Sedimentation Engineering*** (ASCE 1975, pp 126-152). The Limerinos (1970) equation is suggested as a stage-discharge predictor for gravel-bed streams. The Einstein-Barbarossa (1952) method was the first stage-discharge predictor to account for variability in stage due to bed-form roughness by calculating separate hydraulic radii for grain and form contributions. More recently, Brownlie (1981) developed regression equations to calculate a hydraulic radius that accounts for both grain and form roughness in sand-bed streams.

9-11. Brownlie Approach

a. Database. Brownlie's resistance equations are based on about 1000 records from 31 flume and field data sets. The data were carefully analyzed for accuracy and consistency by Brownlie. The resistance equations account for both grain and form roughness, but not bank roughness. The data covered a wide range of conditions: grain size varied between 0.088 and 2.8 mm, and depth ranged between 0.025 and 17 m. All of the data had width-to-depth ratios greater than 4, and the gradation coefficients of the bed material were equal to or less than 5.

b. Regression equations. Brownlie developed separate resistance equations for upper and lower regime flow. The equations are dimensionless, and can be used with any consistent set of units.

Upper Regime:

$$R_b = 0.2836\ d_{50}\ q_*^{0.6248}\ S^{-0.2877}\ \sigma^{0.0813} \tag{9-17}$$

Lower Regime:

$$R_b = 0.3742\ d_{50}\ q_*^{0.6539}\ S^{-0.2542}\ \sigma^{0.1050} \tag{9-18}$$

where

$$q_* = \frac{V\,D}{\sqrt{g\ d_{50}^3}} \tag{9-19}$$

R_b = hydraulic radius associated with the bed

d_{50} = median grain size

S = slope

σ = geometric bed material gradation coefficient

V = average velocity

D = water depth

g = acceleration of gravity

To determine if upper or lower regime flow exists for a given set of hydraulic conditions, a grain Froude number, F_g, and a variable, F_g', were defined by Brownlie:

$$F_g = \frac{V}{\sqrt{g\ d_{50}\left(\frac{\gamma_s - \gamma}{\gamma}\right)}} \tag{9-20}$$

$$F_g' = \frac{1.74}{S^{0.3333}} \tag{9-21}$$

According to Brownlie, upper regime flow occurs if $S >$ 0.006 or if $F_g > 1.25\ F_g'$, and lower regime flow occurs if $F_g < 0.8\ F_g'$. Between these limits is the transition zone.

Section IV
Bed-Load Transport *

* **9-12. General**

Bedload is defined as sediment moving on or near the bed by sliding, rolling, or jumping. Any particle size can move as bed load, depending on hydraulic forces.

9-13. DuBoys' Concept of Bed Load

Between 1879 and 1942 much of the work in sediment transport was influenced by DuBoys. He proposed the idea of a bed shear stress and visualized a process by which the bed material moved in layers. The significant assumptions in the DuBoys approach were that sediment transport could be calculated using average cross-section hydraulic parameters and that transport was primarily a function of the excess shear stress; i.e., the difference between hydraulically applied shear stress and the critical shear stress of the bed material. The general form of the DuBoys equation is

$$q_B = K\tau_o(\tau_o - \tau_c)^m \qquad (9\text{-}22)$$

where

q_B = bed-load transport rate in weight per unit time per unit width

τ_o = hydraulically applied shear stress

τ_c = critical, or threshold shear stress, for the initiation of movement

K and m = constants

The functional relationship between K, τ_c, and grain size was determined experimentally and is presented in ***Sedimentation Engineering*** (ASCE 1975, p 191). In DuBoys' equation m = 1.0. No movement occurs until the bed shear stress exceeds the critical value.

9-14. Einstein's Concept of Particle Movement

A major change in the approach to predicting sediment transport was proposed by Einstein (1950) when he presented a bed-load formula based on probability concepts in which the grains were assumed to move in steps of average length proportional to the sediment size. He describes bed-material transportation as follows:

"The least complicated case of bed-load movement occurs when a bed consists only of uniform sediment. Here, the transport is fully defined by a rate. Whenever the bed consists of a mixture the transport must be given by a rate and a mechanical analysis or by an entire curve of transport against sediment size. For many years this fact was neglected and the assumption was made that the mechanical analysis of transport is identical with that of the bed. This assumption was based on observation of cases where actually the entire bed mixture moved as a unit. With a larger range of grain diameters in the bed, however, and especially when part of the material composing the bed is of a size that goes into suspension, this assumption becomes untenable."

"The mechanical analysis of the material in transport is basically different from that of the bed. This variation of the mechanical analysis will be described by simply expressing in mathematical form the fact that the motion of a bed particle depends only on the flow and its own ability to move, and not on the motion of any other particles." (Einstein 1950).

a. Equilibrium condition. Einstein's hypothesis that motion of a bed particle depends only on the flow and its own ability to move and not on the motion of any other particles allowed him to describe the equilibrium condition for bed-material transportation mathematically as two independent processes: deposition and erosion. He proposed an "equilibrium" condition and defined it as the condition existing when the same number of a given type and size of particles must be deposited in the bed as are scoured from it.

b. Bed-load equation. In Einstein's formulation for bed-load transport, he determined the probability of a particle being eroded from the bed, p, to be

$$\frac{p}{1-p} = A_* \; \Phi_{i}*$$

$$\Phi_i* = \frac{i_B}{i_b}\frac{q_B}{\gamma_s}\left(\frac{\gamma}{\gamma_s-\gamma}\right)^{1/2}\left(\frac{1}{g d_i^3}\right)^{1/2} \qquad (9\text{-}23)$$

where

A* = constant

Φ_i* = bed-load parameter for size class i *

* i_B = fraction of size class i in the bed-load

i_b = fraction of size class i in the bed material

q_B = bed-load transport in weight per unit time and width

d_i = grain diameter of size class i

He then reasoned that the dynamic lift forces on a particle are greater than particle weight when the probability to go into motion is greater than unity. Assuming a normal distribution for the probability of motion yields

$$p = 1 - \frac{1}{\sqrt{\pi}} \int_{\eta_o}^{\eta} e^{-t^2} dt \qquad (9\text{-}24)$$

$$\eta_o = -B_* \Psi_{i*} - 2.0$$

$$\eta = B_* \Psi_{i*} - 2.0$$

where

$B*$ = a constant

Ψ_i* = dimensionless flow intensity parameter

t = variable of integration

Ψ_i* is a function of grain size, hydraulic radius, slope, specific weight, and viscosity. Correction factors are applied to account for hiding and pressure variations due to the composition of the bed-material mixture. Setting the probability of erosion equal to the probability of motion yields the Einstein bed-load function

$$1 - \frac{1}{\sqrt{\pi}} \int_{\eta_o}^{\eta} e^{-t^2} dt = \frac{A_* \Phi_*}{1 + A_* \Phi_*} \qquad (9\text{-}25)$$

The equation can be transformed into the following and solved for sediment transport rate, q_B

$$i_B q_B = i_b \Phi_* \gamma_s d_i \sqrt{g d_i \left(\frac{\gamma_s - \gamma}{\gamma} \right)} \qquad (9\text{-}26)$$

where $\Phi*$ is a function of $\Psi*$ which is determined using empirically derived graphs provided by Einstein (1950) or ASCE (1975, pp 195-200).

c. Limitations. The dependence of the Einstein method on these empirical graphs, which were derived from limited data, limits the applicability of the method. The important contributions of this work were the introduction of the probability concept for bed-load movement, the identification of processes influencing entrainment and transport of sediment mixtures, and a formulation of the interactions. Einstein was aware of the limitations of his method and did not intend that it should be considered as a universal one.

Section V
Suspended Sediment Transport

9-15. Concentration Equation

The most important process in maintaining sediment in suspension is flow turbulence. In steady turbulent flow, velocity at any given point will fluctuate in both magnitude and direction. Turbulence is greatest near the boundary where velocity changes are the greatest. When dye is injected instantaneously at a point in a turbulent flow field, the cloud will expand as it is carried downstream at the mean velocity. This process is called diffusion and is the basis for the analytical description of sediment suspension. The one-dimensional sediment diffusion equation balances the upward flow of sediment due to diffusion with the settling of the sediment due to its weight

$$C \omega + \varepsilon_s \frac{\partial C}{\partial y} = 0 \qquad (9\text{-}27)$$

where

C = sediment concentration

ω = settling velocity

ε_s = sediment diffusion coefficient

y = depth *

* For boundary roughness dominated flows, it is common practice to assume that the sediment diffusion coefficient is equal to the momentum diffusion coefficient, ε_m, which can be described by

$$\varepsilon_s = \varepsilon_m = \kappa\, U* \frac{y}{D} (D - y) \qquad (9\text{-}28)$$

where

κ = Von Karman constant

$U*$ = shear velocity

D = total water depth

Integration yields the Rouse equation:

$$\frac{C_y}{C_a} = \left(\frac{D - y}{y} \; \frac{a}{D - a} \right)^z \qquad (9\text{-}29)$$

$$z = \frac{\omega}{\kappa\, U*} \qquad (9\text{-}30)$$

where

a = reference elevation

C_a = concentration at reference elevation

C_y = concentration at depth y

The equation gives the concentration in terms of C_a , which is the concentration at some arbitrary level $y = a$. This requires foreknowledge of the concentration at some point in the vertical. Typically, this point is assumed to be close to the bed and C_a is assumed to be equal to the bed-load concentration. One problem with this equation is that concentration approaches infinity as y approaches zero. Therefore, the equation cannot be used to calculate the total sediment load from the bed to the surface. A graph of the Rouse suspended load distribution equation is shown in Figure 9-6.

9-16. Suspended Sediment Discharge

Suspended sediment discharge is calculated from the concentration profile using the following equation:

$$q_s = \int_{y=y_o}^{D} C_y u \, dy \qquad (9\text{-}31)$$

where u is the local velocity. Solution of this equation requires an analytical description of the vertical velocity distribution.

a. Einstein's approach. Einstein (1950) assigned the lower limit of integration, $y_o = 2d_i$, and called this the thickness of the bed layer. He assumed that C_a was equal to the bed-load concentration. He used Keulegan's logarithmic velocity distribution equations to determine velocity. Since this work was done prior to the common usage of computer, Einstein prepared tables for the solution of the integral. These are found in Einstein (1950) and ASCE (1975) as well as other sediment transport texts. Total sediment transport can be calculated as a function of the bed-load concentration. The equation for total bed-material transport for particle size i is

$$q_i = q_{Bi} + q_{si} \qquad (9\text{-}32)$$

$$q_{Bi} = i_b\, \Phi*_i \gamma_s d_i \sqrt{g d_i \left(\frac{\gamma_s \gamma}{\gamma} \right)} \qquad (9\text{-}33)$$

$$q_{si} = i_b C_{ai} \int_{y=y_o}^{D} \left(\frac{D-y}{y} \; \frac{a}{D-a} \right)^z u*\, 5.75 \log \left(\frac{30.2y}{\Delta} \right) dy \qquad (9\text{-}34)$$

where

a = thickness of the bed-load layer (Einstein considered $a = 2d_i$)

C_a = concentration in bed-load layer

d_i = geometric mean of particle diameters in each size class i

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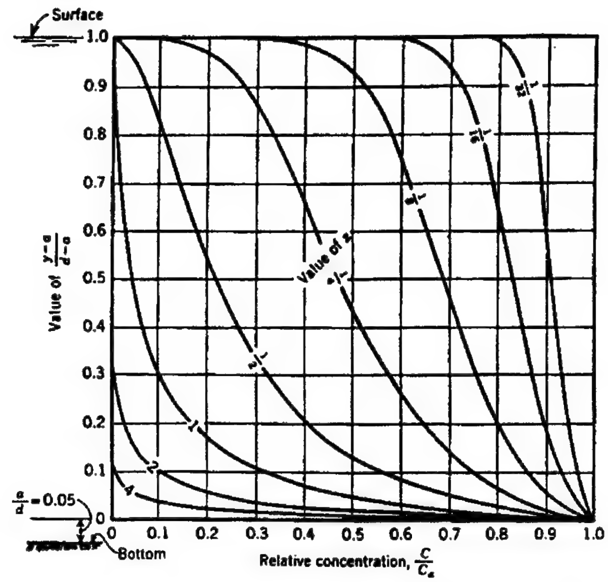

Figure 9-6. Rouse's suspended sediment concentration distribution for a/D = 0.5 and several values of z (ASCE 1975, p 77)

D = flow depth, bed to water surface

i = size class interval number

i_b = fraction of size class i in the bed

κ = von Karman constant = 0.4 in clear water

q_i = unit total bed material load in size class i

q_{si} = unit suspended bed material load in size class i

q_{Bi} = unit bed-load in size class i

y = any point in the flow depth measured above the bed

z = slope of the concentration distribution ($\omega_i/\kappa u_*$)

u_* = bed shear velocity

ω_i = settling velocity for grains of sediment in class interval i

Δ = apparent grain roughness diameter of bed surface

The total unit sediment discharge of the bed-material load is the sum of discharges for all particle sizes in the bed.

$$q_s = \Sigma_1^N q_{si} \tag{9-35}$$

where n = number of size classes

b. Brooks approach. Brooks (1965) developed a graph that can be used to calculate suspended sediment transport if the sediment concentration at middepth is known. Using the Rouse equation, Brooks assigned $a = 0.5$ D. The lower limit of integration, y_o, was determined to be the depth where $u = 0$. Brooks used a power law velocity distribution equation and numerical integration to develop the curve shown in Figure 9-7. This figure can be used to determine total suspended sediment concentration when the concentration at middepth, the average velocity V, and the shear velocity U^* are known.

Section VI
Selecting a Sediment Transport Function

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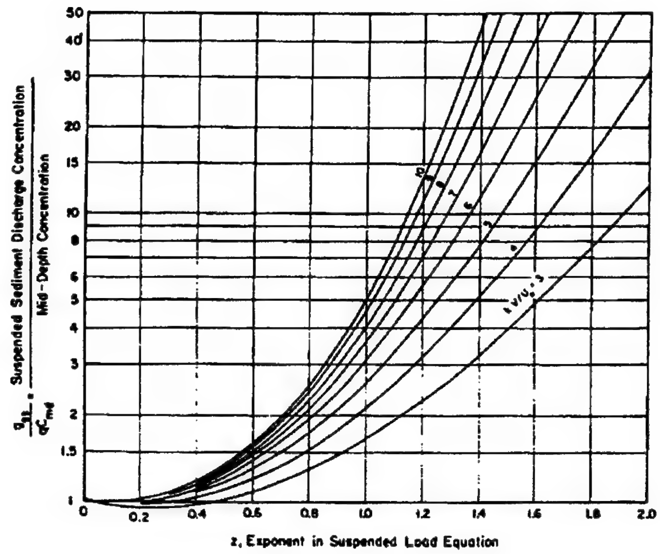

Figure 9-7. Brooks curve for suspended sediment concentration (ASCE 1975)

9-17. General

Most sediment transport functions predict a rate of sediment transport for a given set of steady-state hydraulic and bed-material conditions. Typically, hydraulic variables are laterally averaged. Some sediment transport equations were developed for calculation of bed load only, and others were developed for calculation of total bed material load. This distinction can be critical in sand-bed streams, where the suspended bed-material load may be orders of magnitude greater than the bed load. Another important difference in sediment transport functions is the manner in which grain size is treated. Most sediment transport functions were developed as single-grain-size functions, usually using the median bed-material size to represent the total bed. Single-grain-size functions are most appropriate in cases where equilibrium sediment transport can be assumed, i.e. when the project will not significantly change the existing hydraulic or sediment conditions. When the purpose of the sediment study is to evaluate the effect of a project on sediment transport characteristics (i.e., the project, or a flood, will introduce nonequilibrium conditions), then a multiple-grain-size sediment transport equation should be used. Multiple-grain-size functions are very sensitive to the grain-size distribution of the bed material. Extreme care must be exercised in order to ensure that the fine component of the bed-material gradation is representative of the bed surface for the specified discharge. This is very difficult without measured data. For this reason Einstein (1950) recommended ignoring the finest 10 percent of the bed material sample for computation of bed-material load with a multiple-grain-size function. Frequently, single-grain-size functions are converted to multiple-grain-size functions simply by calculating sediment transport using geometric mean diameters for each size class in the bed (sediment transport potential) and then assuming that transport of that size class (sediment transport capacity) can be obtained by multiplying the sediment transport potential by the bed fraction. This assumes that each size class fraction in the bed acts independent of other size classes on the bed, thus ignoring the effects of hiding, which can produce unreliable results.

9-18. Testing

It is important to test the predictive capability of a sediment transport equation against measured data in the project stream or in a similar stream before its adoption for use in a sediment study. Different functions were developed from different sets of field and laboratory data and are better suited to some applications than others. Different functions may give widely differing results for a

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* specified channel. Experience with sediment discharge formulas can be summed up in Figure 9-8.

9-19. Sediment Transport Equations

A generalized sediment transport equation can be presented in a functional form:

$$Q_s = f(V, D, S_e, B, d_e, \rho_s, G_{sf}, d_s, i_b, \rho, T) \quad (9\text{-}36)$$

where

B = effective width of flow

D = effective depth of flow

d_e = effective particle diameter of the mixture

d_s = geometric mean of particle diameters in each size class i

Q_s = total bed material discharge rate in units of weight divided by time

G_{sf} = grain shape factor

i_b = percentage of particles of the ith size class that are found in the bed expressed as a fraction

S_e = slope of energy line

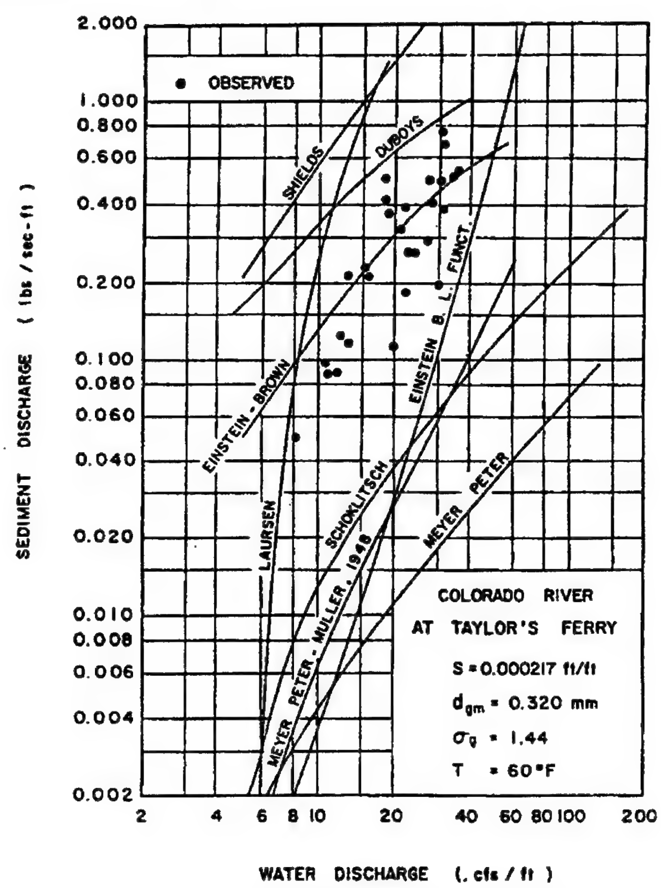

Figure 9-8. Sediment discharge rating curve, Colorado River (ASCE 1975)

*

* ρ = density of fluid for other than temperature effect

ρ_s = density of sediment particles

T = water temperature

V = average flow velocity

Of particular interest are the groupings of terms: hydraulic parameters (V, D, S_e, B), sediment particle parameters (d_e, ρ_s, G_{sf}), sediment mixture parameters (d_s, i_b), and fluid properties (ρ, T).

a. Processes. Although Einstein's (1950) work is classic and presents a complete view of the processes of equilibrium sediment transportation, it is more useful for understanding those processes than for application. Many other researchers have contributed sediment transport functions - always attempting to arrive at one which is always dependable when compared against field data. The choices are too numerous to name, and yet no single function has been proved superior to the others for the general case. The following general guidelines are given to aid in the selection of a transport function. However, it is important to confirm the selection using data from the project site. In the absence of such confirmation, the scatter between calculated values, similar to that shown in Figure 9-8, may be used in establishing a sensitivity range or a risk and uncertainty factor.

b. Colby (1964). The Colby equation has been used successfully on a limited class of shallow sand-bed streams with high sediment transport. The Colby function was developed as a single-grain-size function for both bed load and suspended bed-material load. Its unique feature is a correction factor for very high fine sediment concentrations. This correction factor may be used with other sediment transport equations and has been incorporated into the HEC-6 numerical model where it is used with all sediment-transport equations.

c. Einstein (1950). The Einstein equation has application for both sand and gravel bed streams. It is a multiple-grain-size sediment transport function that calculates both bed-load and suspended bed-material load. The hiding factor in the original equation has been modified by several investigators (Einstein and Chien 1953; Pemberton 1972; and Shen and Lu 1983) to improve performance on specific studies.

d. Laursen-Madden (Madden 1993). The Laursen (1958) sediment transport equation, which was based on flume data, was modified by Madden in 1963 based on data from the Arkansas River and again in 1985 using additional data from other sand-bed rivers. The equation calculates both bed-load and suspended bed-material load. It is a multiple-grain-size function, but it does not have a hiding factor. This feature makes its application in streams with a wide range of grain sizes questionable. The 1963 equation has been used successfully on large and intermediate size sand-bed rivers. The newer equation should be applicable in stream channels having sizes from sand to medium gravels.

e. Meyer-Peter and Muller (1948). This equation was developed from flume data and was developed as a multi-grain-size function, although it is frequently applied as a single-grain-size function. Sediment was transported as bed load in the Meyer-Peter and Muller flume. Its applicability is for bed-load transport in gravel-bed streams. It has been found to significantly underestimate transport of larger gravel sizes in several studies.

f. Toffaleti (1968). This multiple-grain-size function has been successfully used on many large sand-bed rivers. It calculates both bed load and bed-material suspended load and is based on extensive sand-bed river and flume data. Its formulation follows that of Einstein; however, there are significant differences. The Toffaleti equation generally underestimates the transport of gravel size classes. However, it has been combined with the Meyer-Peter and Muller equation in HEC-6 and SAM to provide an equation with more potential to transport a wider range of size classes.

g. Yang (1973, 1984). Yang developed two regression equations, one for sand and one for gravel, from extensive measured data on a wide variety of streams. This is a single-grain-size equation, and when applied as a multiple-grain-size function in HEC-6 or SAM it is done so without a hiding factor. The function is not as sensitive to grain size as other functions and, therefore, is less likely to produce wide variations in calculated sediment transport. It is most applicable to intermediate to small sand bed streams with primarily medium to coarse sand beds. It would not be appropriate if significant armoring or hydraulic sorting of the bed is expected.

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* **9-20. Guidance Program in SAM**

A guidance module was included in the SAM hydraulic design package to aid in the selection of a sediment transport function. The significant hydraulic and sediment variables of slope, velocity, width, depth, and median grain size applicable to a given stream are provided to the computer program. The program then checks the given data against 17 sets of field data collected by Brownlie (1983) and looks for a river with similar characteristics. Ten sediment transport equations were tested with each of the 17 data sets and the best three were determined. The program then reports to the user which are the three best sediment transport equations for each of the data sets with hydraulic characteristics that matched the given stream.

9-21. Procedure for Calculating Sediment-Discharge Rating Curve

The steps in calculating a sediment-discharge rating curve from the bed-material gradation are:

a. Assemble field data (cross sections and bed gradations).

b. Develop representative values for hydraulic variables and for bed gradation from the field measurements.

c. Calculate the stage-discharge rating curve accounting for possible regime shifts due to bed-form change.

d. Calculate the bed-material sediment-discharge rating curve using hydraulic parameters from the stage-discharge calculation.

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Chapter 10
Nonequilibrium Sediment Transport

Section I
Introduction

10-1. General

Nonequilibrium sediment transport refers to cases where the outflowing sediment discharge from a reach does not equal the inflowing sediment discharge to that reach. All five processes of sedimentation: erosion, entrainment, transport, deposition, and consolidation are active. The nonequilibrium sediment transport condition results in an unstable streambed elevation. In such cases a numerical sedimentation model provides the computational framework for analysis.

10-2. Specific Gage Plots

Nonequilibrium sediment transport results in either an aggrading or a degrading streambed. A simple graphical technique that is useful for quantifying the nonequilibrium condition is a specific gage plot, Figure 10-1. Such a graph is made by selecting a water discharge and plotting its stage versus time from the measured stage-discharge rating curves. When there is a definite trend over time, sediment inflow to the reach is not in equilibrium with sediment outflow.

10-3. Equilibrium versus Nonequilibrium Conditions

Although sediment transport formulas are used in an analysis of nonequilibrium conditions, there are significant differences between the calculations for equilibrium sediment transport and calculations for the nonequilibrium condition. Table 10-1 summarizes those differences. The words "equilibrium" and "nonequilibrium" in this table refer to the exchange of sediment particles between the flow field and the bed of the cross section. Whereas the bed is the only source of sediment to a sediment transport formula, the sources for a nonequilibrium sediment condition include the bed, upstream reach, tributaries, and bank caving.

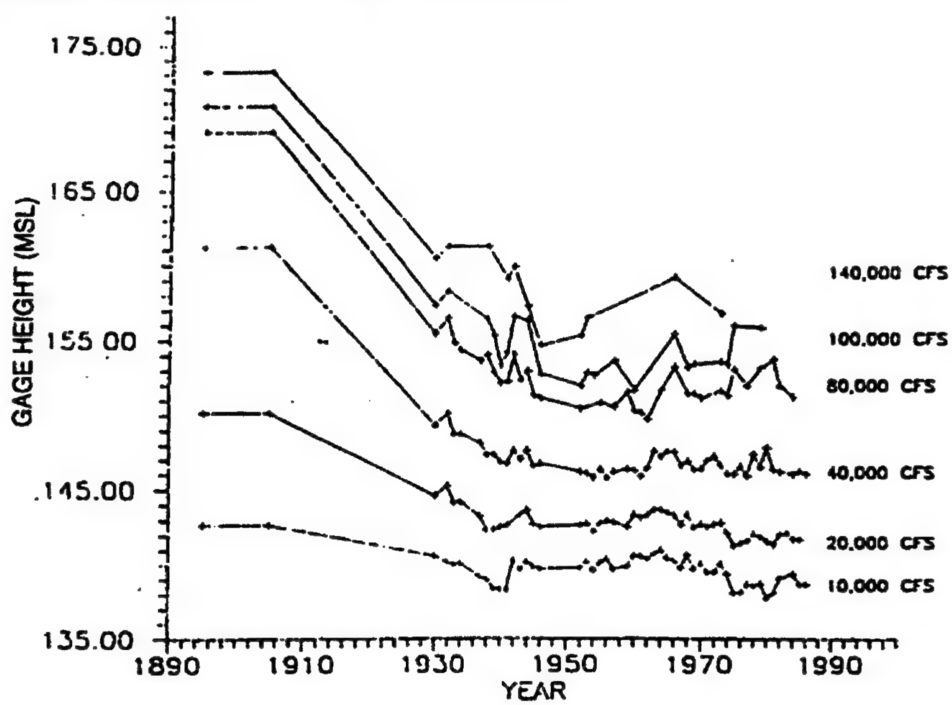

Figure 10-1. Specific gage plot

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Table 10-1
Differences Between Calculations for Equilibrium Sediment Transport and Nonequilibrium Sediment Transport

Sediment Discharge Formula	Nonequilibrium Models
Require flow intensity, bed roughness, particle density, and bed surface gradation	Require flow intensity, bed roughness, particle density, both surface and subsurface bed gradations, inflowing sediment load, geometry over long distances, and identification of bedrock outcrops.
Calculate the equilibrium condition	Calculate both the equilibrium condition and the changes in bed profile due to sediment inflow deficit or excess.
Functional only for the bed-material load	Functional for both bed-material and wash loads
	In the case of sand moving over a gravel bed, models will calculate both the quantity of sediment load moving and bed surface gradation required to sustain it

10-4. Mass Balance Models

The nonequilibrium condition is typically addressed using numerical sedimentation modeling. For most engineering studies, this modeling does not require tracing the motion of individual particles. Rather, it requires calculating the impact of flow intensity on bed particle behavior subject to particle size and availability. The objective is to calculate changes in the bed surface elevation in response to nonequilibrium sediment conditions and to feed those changes back into the calculation of the flow intensity-sediment load parameters. However, questions dealing with sediment quality often cannot be addressed without tracing the path of the sediment particles.

10-5. Numerically Modeling the Nonequilibrium Condition

The nonequilibrium problem can best be analyzed using a control volume approach. This allows the engineer to partition the river into reaches so both the bed and the inflowing sediment load to the reach are sediment sources to the calculations in that reach. Nonequilibrium conditions will transfer from one reach to the next because sediment movement tends to be highly variable in both discharge rate and particle size distribution. The most significant feature of a mobile-bed numerical model is its formulation of the sediment continuity equation which handles the exchange rate between the water column and the bed surface. It should account for sediment transport by size class and maintain a continuous account of the gradation in the streambed and on its surface. The numerical model should also account for: bed roughness, which can vary with discharge; bed armoring and sorting; bed surface thickness and porosity; and bed compaction. It should be recognized that there are major knowledge gaps related to sedimentation processes. For example, the lack of understanding of the bed sorting process and its effect on the transport of sediment mixtures makes it difficult to formulate a numerical representation of the process. Also, the fact that sediment is transported primarily in the channel requires that mobile bed computations maintain an accurate distribution of flow between the left overbank, channel, and right overbank at the cross section for which the computation is being made as well as a history of how the flow arrived at that location in the cross section whereas it is only necessary to balance energy in a fixed bed computation to solve for the water surface elevation.

Section II
Theoretical Basis

10.6. Equations of Flow and Continuity

The one-dimensional partial differential equations of gradually varied unsteady flow in natural alluvial channels are: (a) the equation of motion for the water-sediment mixture, (b) the equation of continuity for water, and (c) the equation of continuity for sediment. The system of equations for unsteady flow are established by considering the conservation of mass (both sediment and water) and momentum in an infinitesimal space between two channel sections.

Equation of Motion

$$\frac{\partial(\rho Q)}{\partial t} + \frac{\partial(\rho Q V)}{\partial x} + gA\,\frac{\partial(\rho\, y)}{\partial x} = \rho g A(S_o - S_f + D_l) \tag{10-1}$$

*

* Water Continuity

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q_w = 0 \qquad (10\text{-}2)$$

Sediment Continuity

$$\frac{\partial Q_s}{\partial x} + (1-P)\frac{\partial A_d}{\partial t} - q_s = 0 \qquad (10\text{-}3)$$

where

A = end area of channel cross section

A_d = volume of sediment deposited on the bed per unit length of channel

D_l = momentum loss due to lateral inflow

g = acceleration of gravity

P = porosity of the bed deposit (volume of voids divided by the total volume of sample)

Q = water discharge

Q_s = sediment discharge

q_s = lateral sediment inflow per unit length of channel, outflow (-), inflow (+)

q_w = lateral water inflow per unit length of channel, outflow (-), inflow (+)

S_f = friction slope

S_o = slope of channel bottom

t = time

x = horizontal distance along the channel

V = flow velocity

y = depth of flow

ρ = density of the water

10-7. Assumptions

The following assumptions are made in deriving these equations.

a. The channel is sufficiently straight and uniform in the reach so that the flow characteristics may be physically represented by a one-dimensional model.

b. The velocity is uniformly distributed over the cross section.

c. Hydrostatic pressure prevails at every point in the channel.

d. The water surface slope is small.

e. The density of the sediment-laden water is constant over the cross section.

f. The unsteady flow resistance coefficient is assumed to be the same as for steady flow in alluvial channels and is approximated from resistance equations applicable to alluvial channels or from field survey.

10-8. The Boundary Value Problem

With this system of equations there are three more unknowns than equations. The solution is obtained by prescribing the value of three variables on the inflow/outflow boundaries. This type of solution is called a boundary value problem. The boundary conditions are: (a) the water discharge, (b) the stage, and (c) the sediment concentration. These are prescribed for each point where water crosses the boundary of the study area. The solution of the system of equations is then possible. Depth, discharge, and sediment concentration at every computation point in the model can be calculated. The solution of the equations is deterministic, but the boundary conditions are not. It is important that the engineer select boundary conditions which depict historic behavior for model confirmation. Sometimes a different set of boundary conditions are required reflecting future conditions to model future prototype behavior.

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* *Section III*
Data Requirements

10-9. General Data Requirements

Two types of data are required for a numerical model study of a nonequilibrium stream. One type is used to define the behavior of the prototype. The other type is required to construct and adjust the numerical model. The first is summarized for completeness in this paragraph; the second is presented in more detail in following paragraphs. The ***project area and study area boundaries*** should be marked on a project map to delineate the area needing data. Lateral limits of the study area and the tributaries should be identified. ***Bed profiles*** from historical surveys in the project area are extremely valuable for determining the historical trends which the model must reconstitute. ***Aerial photographs*** and aerial mosaics of the project area are very useful for identifying historical trends in channel width, meander wave length, rate of bank line movement, and land use in the basin. ***Stream gage records*** establish the annual water yield to the project area and the water yield from it. They are also useful for establishing the hydraulic parameters of depth, velocity, roughness, and the trends in the stage-discharge curve in, or close to, the project reach. It is important to work with measured data. The "extrapolated" portion of a rating curve should not be regarded as measured data. Be aware that measured data are also subject to error. ***Reconnaissance of the project reach*** is a valuable aid for determining channel morphology, geometric anomalies, the existence of structures, and sediment characteristics of the channel. Include geotechnical and environmental specialists in a field reconnaissance if possible. Document these observations of the prototype in project reports. View as much of the prototype as is feasible and not just bridge crossings. ***Hydraulic data*** such as measured water surface profiles, velocities, and flood limits in the project reach are extremely valuable. Local action agencies, newspapers, and residents along the stream are sources of information when field measurements are not available.

10-10. Geometric Data

The purpose of mobile-bed calculations is to determine the water-surface elevation and the bed-surface elevation as they change over time. It is necessary to prescribe the starting geometry. After that, computations will aggrade or degrade the cross sections in response to mobile bed theory. The cross sections never change locations.

a. As in fixed bed calculations, it is important to locate the cross sections so that they model the channel contractions and expansions. It is particularly important in mobile boundary modeling to also recognize and set conveyance limits. That is, when flowing water does not expand to the lateral dimensions of a cross section in the prototype then conveyance limits should be set in the model.

b. There is no established maximum or minimum spacing for cross sections. Some studies have required distances as short as a fraction of the river width. Others have allowed spacing sections 10-20 miles apart. The objective is to develop a model that will reconstitute the historical response of the streambed profile. The usual approach is to start with the same geometry that was developed for fixed bed calculations. Note that, as most fixed bed data sets are prepared to analyze flood flows, they may be biased toward constrictions such as bridges and deficient of reach-typical sections that are important for long-term river behavior. There may also be cases when cross sections must be eliminated from the data set to preserve model behavior, such as a deep bend or junction section where the shape is molded by multi-dimensional hydrodynamics and not by one-dimensional hydraulic-sediment transport.

c. Use of river mile as the cross-section identification number is recommended. It is much easier to use or modify data when the cross sections are referenced by river mile rather than using an arbitrary section number.

10-11. Bed-Material Data

The bed-material reservoir is the space in the bed of the stream from which sediment can be eroded or onto which it can be deposited. This reservoir occupies the entire width of the channel, and in some cases the width of the overbank too. However, it might have 'zero' depth in the case of a rock outcrop. It is necessary to determine the gradation of sediment in that bed sediment reservoir and prescribe it for a numerical model. Bed-material sampling techniques are discussed in paragraph 8-13 of this manual. It is important to account for vertical, lateral, and horizontal variations in the bed-material reservoir. The gradation used in a numerical model should be "representative" of the reach and appropriate for addressing the engineering question at hand. For example, in one study two samples were taken in the dry at 27 cross sections spaced over a 20-mile reach of the creek. One was near the water's edge and the other was from the point *

* bar deposits about half the distance to the bank. These samples were sieved separately, and the resulting gradations plotted, as shown in Figures 10-2 and 10-3. Results from the water's edge samples were used to test for erosion because they were coarser than the midbar samples. The midbar samples were used to test for transport rates.

10-12. Hydrologic Data

Although instantaneous peak water discharges may be of interest, they are not adequate for movable bed analyses because time is a variable in the governing equations, and sediment volumes rather than instantaneous rates of movement create channel changes. Consequently, the water discharge hydrograph must be developed. This step can involve manipulations of measured flows, or it can require a calculation of the runoff hydrograph. Historical flows are needed to reconstitute behavior observed in the river, but future flows are needed to forecast the future streambed profile.

a. Hydrograph. The length of the hydrograph period is important. Trends of a tenth of a foot per year become significant during a 50- or 100-year project life. A long period hydrograph can become a computation burden. In some cases data compression techniques may be useful. As an example, Figure 10-4 shows how a year of mean daily flows could be represented by fewer discharges of larger duration. A computer program developed at WES, called the "Sediment Weighted Histograph Generator" was developed to preserve volumes while aggregating the energy of a varying hydrograph into extended numbers of days.

b. Tributaries. Tributaries are lateral inflow boundary conditions. They should be located, identified, and grouped as required to define water and sediment distributions. The locations should be shown on the cross-section locations. It is important that the water and sediment inflows from all gaged and ungaged areas within the study reach be included. Keep in mind that a 10 percent increase in water discharge could result in a 20 percent or greater increase in bed-material transport capacity. Often the tributaries are not gaged, thus requiring water distribution by analytical means. Drainage-area ratios may be used in some cases; however, use or development of a hydrologic model of the basin may be necessary.

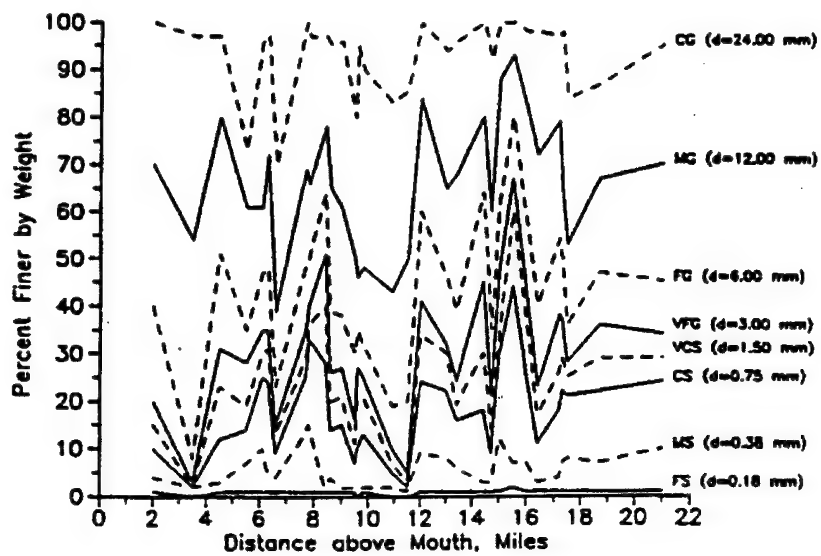

Figure 10-2. Bed-surface gradations based on water's edge samples

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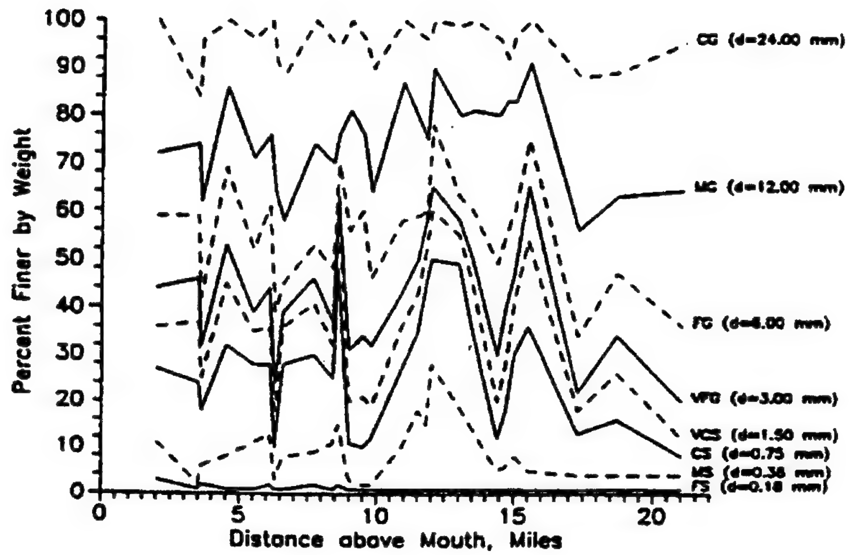

Figure 10-3. Bed-surface gradations based on midbar samples

Describe how inflows were accommodated for those tributaries not specifically included.

c. Tailwater elevation. The water-surface elevation at the downstream boundary of the project must be specified. It is referred to as a tailwater elevation because it serves the same purpose as a tailgate on a physical model. It can be a stage-discharge rating curve, or it can be a stage hydrograph. The rating curve can be calculated assuming normal depth if the boundary is in a reach where friction is the control and the water surface slope is constant for the full range of discharges. When a backwater condition exists, such as at the mouth of a tributary or in a reservoir, then use a stage hydrograph as the boundary condition. Be sure it covers the same period of time as the inflow hydrographs.

10-13. Sediment Inflow Data

a. Inflowing sediment concentrations. Occasionally, measured suspended sediment concentrations, expressed as milligrams per liter, are available. These are usually plotted against water discharge and often exhibit very little correlation with discharge; however, use of such graphs is encouraged when developing or extrapolating the inflowing sediment data. As the analysis proceeds, it is desirable in most situations to convert the concentrations to sediment discharge in tons/day and to express that as a function of water discharge as shown in Figure 10-5. A scatter of about 1 log cycle is common in such graphs. The scatter is smaller than on a concentration plot because water discharge is being plotted on both axes. The scatter may be the result of seasonal effects, random measurement errors, changes in watershed or hydrology during the measurement period, or other sources. The engineer should carefully examine these data and attempt to understand the shape and variance of the relationship.

b. Grain size classes. The total sediment discharge should then be partitioned into size classes for the mobile bed computations. Table 10-2 shows a procedure developed for the Clearwater River at Lewiston, Idaho. The data in this table come from measured bed load and measured suspended load. Figure 10-6 is the graph of that data set. Note that, due to the availability of various size fractions in the bed and the suspended load gradation for a given flow, the transport rate does not necessarily decrease with increasing particle size.

c. Calculating sediment inflow with transport theory. When no suspended sediment measurements are

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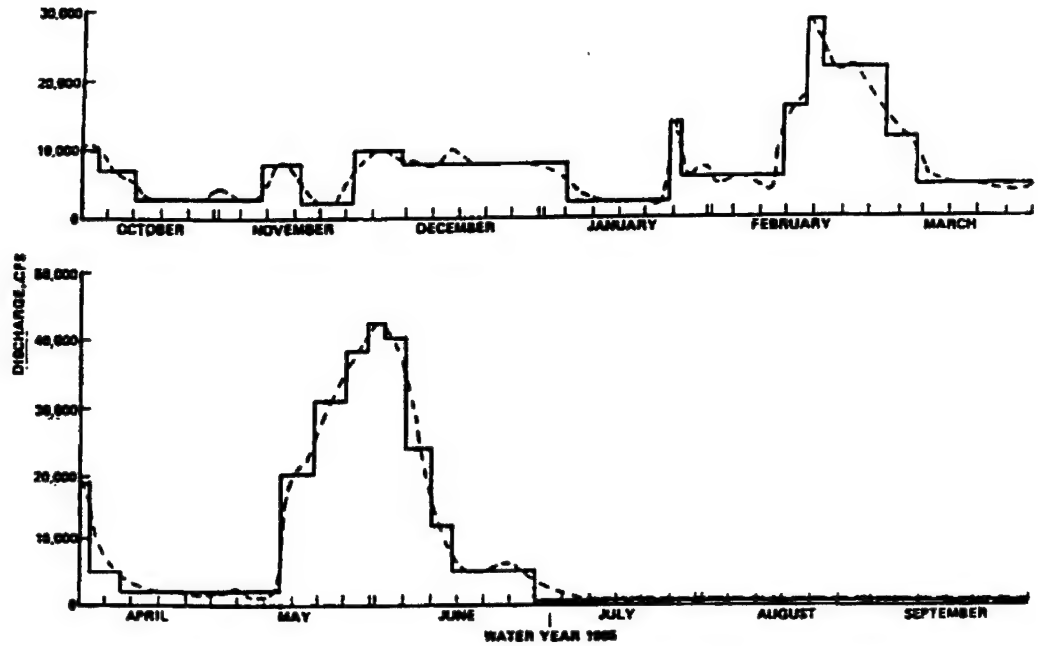

Figure 10-4. Water discharge histograph

available, the inflowing sediment boundary condition must be calculated. That is possible for sand and gravel using mobile bed hydraulics and sediment transport theory. There is no comparable theory for the wash load inflow. When making a calculation for the boundary condition, select the reach of channel very carefully. It should be one approaching the project which has a slope, velocity, width, and depth typical of the hydraulics which are transporting the sediment into the project reach. It should also have a bed surface that is in equilibrium with the sand and gravel discharge being transported by the flow. Having located such a reach, select a representative cross section for that reach. Make the calculation by particle size for the full range of water discharges in the study plan.

d. Importance of bed-material designation. In the calculation of sediment transport, the designated bed gradation controls the calculated sediment discharge. The rate of transport increases exponentially as the grain size decreases, as shown in Figure 10-7. Therefore, bed-material gradations must be determined carefully. Techniques for selecting a representative sample are discussed in paragraph 8-13 of this manual. Due to the sensitivity of transport calculations to the grain size, especially the finer sizes, Einstein (1950) recommended excluding the finest 10 percent of the sampled bed gradation for calculation of the total bed-material load.

e. Sediment inflow from tributaries. The sediment inflow from tributaries is more difficult to establish than it is for the main stem because there is usually less data. The recourse is to assess each tributary for sediment delivery potential during the site reconnaissance. For example, look for a delta at the mouths of the tributaries. Look for channel bed scour or deposition along the lower end of the tributary. Look for drop structures or other controls that would aid in stabilizing a tributary. Look for significant deposits if the tributaries have concrete lining. These observations guide the development of tributary sediment discharges.

10-14. Temporal Variations

The discussion assumes the historical water inflows, sediment concentrations, particle sizes, and tailwater rating curve will not change in the future. That assumption should be justified for each project and the appropriate modifications made.

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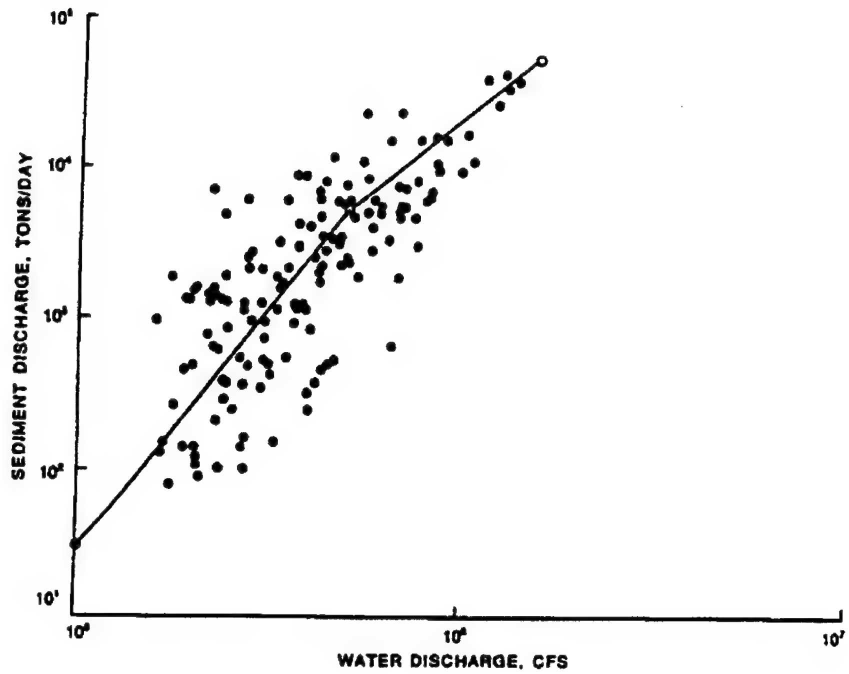

Figure 10-5. Sediment-discharge rating curve

10-15. Data and Profile Accuracy

Agreement between calculated and measured water surface elevations of +/- 0.5 ft are usually satisfactory in natural rivers. Profiles of the average bed elevation may exhibit little or no correlation with the prototype, but cross-sectional area changes should correlate with prototype behavior.

Section IV
Model Adjustment and Circumstantiation

10-16. Model Performance

Prior to using a numerical model for the analysis of a project, the model's performance needs to be confirmed. Ideally this consists of a split record test: an adjustment test and a circumstantiation test. During the adjustment test, initial boundary conditions and hydraulic coefficients are chosen such that computed results reproduce field measurements within an acceptable error range. Computed results should be compared with field measurements to identify data deficiencies or physically unrealistic values. In order to improve the agreement between observed and calculated values, model coefficients and boundary conditions are adjusted, but only within the bounds associated with their uncertainty. Model adjustment does not imply the use of physically unrealistic coefficients to force a poorly conceived model into reproducing prototype measurements. If a discrepancy between model results and prototype data persists, then either there is something wrong with the model's representation of the dominant physical processes (a model deficiency as a result of limiting assumptions), there is a deficiency in the representation of field data as model input (an application error), and/or there is something wrong with the measured data (a data deficiency). Therefore, if model adjustment cannot be accomplished through the usage of physically realistic values of the coefficients, the measured prototype data should be checked for possible errors and the numerical model (input data, basic equations, and solution algorithm) should be examined. One caution is to recognize the time scale factor. For example, when the boundary concentrations are increased, there should be a deposition trend in the interior of the model. When such a trend does not occur, it may signify that more time is needed. Extend the hydrograph until the deposition trend shows up in the calculated results. *

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Table 10-2
Distribution of Sediment Load by Grain Size Class

Water Discharge: 35,000 cfs

Total Bed Load, tons/day..................130
Total Suspended Load, tons/day.....1,500
Total Sediment Load........................1,630

Grain Size Diameter, mm	Classification	Percent Bed Load	Bed Load tons/day	Percent Sus-pended Load	Suspended Load, tons/day	Total Load Column (4) + (6) tons/day
(1)	(2)	(3)	(4)	(5)	(6)	(7)
< 0.0625	silt and clay	0.04	0.05	54	810	810
0.0625 - 0.125	very fine sand	0.10	0.13	10	150	150
0.125 - 0.25	fine sand	2.75	4.00	13	195	199
0.25 - 0.50	medium sand	16.15	21.00	19	285	306
0.50 - 1.0	coarse sand	13.28	17.00	4	60	77
1.0 - 2.0	very coarse sand	1.19	2.00			2
2 - 4	very fine gravel	1.00	1.00			1
4 - 8	fine gravel	1.41	2.00			2
8 - 16	medium gravel	2.34	3.00			3
16 - 32	coarse gravel	6.33	8.00			8
32 - 64	very coarse gravel	23.38	30.00			30
> 64	cobbles and larger	32.03	42.00	—	—	42
TOTAL		100.00	130.18	100	1,500	1,630

Notes:

[1] The distribution of sizes in the bed load is usually computed using a bed-load transport function and field samples of bed-material gradation. The bed-load rate is rarely measured and may have to be computed.

[2] The suspended load and its gradation can be obtained from field measurements. The bed-material portion of the suspended load may be calculated using a sediment transport function, but the wash load can only be obtained through measurement.

10-17. Model Adjustment

Model adjustment is the process of coefficient selection and input data modification that produces model simulation results that agree with prototype behavior. Adjustment involves the selection of values for fixed and movable bed coefficients plus the art of transforming three-dimensional prototype measurements into "representative data" for one-dimensional computations. ***Fixed bed coefficients*** are: roughness coefficients, which do not depend on the characteristics of the movable boundary; coefficients of contraction; coefficients of expansion; and ineffective flow area delineation. ***Movable bed coefficients*** are roughness coefficients for the movable bed, which may depend on the rate of sediment transport. Development of ***representative data*** for one-dimensional computations is not done by simply averaging a collection of samples. In terms of geometry, it is the selection of cross sections which produces the one-dimensional approximation of hydraulic parameters that will reconstitute prototype values in such a way that water and sediment movement in the model mimics that in the prototype. In terms of sedimentation, it requires the selection

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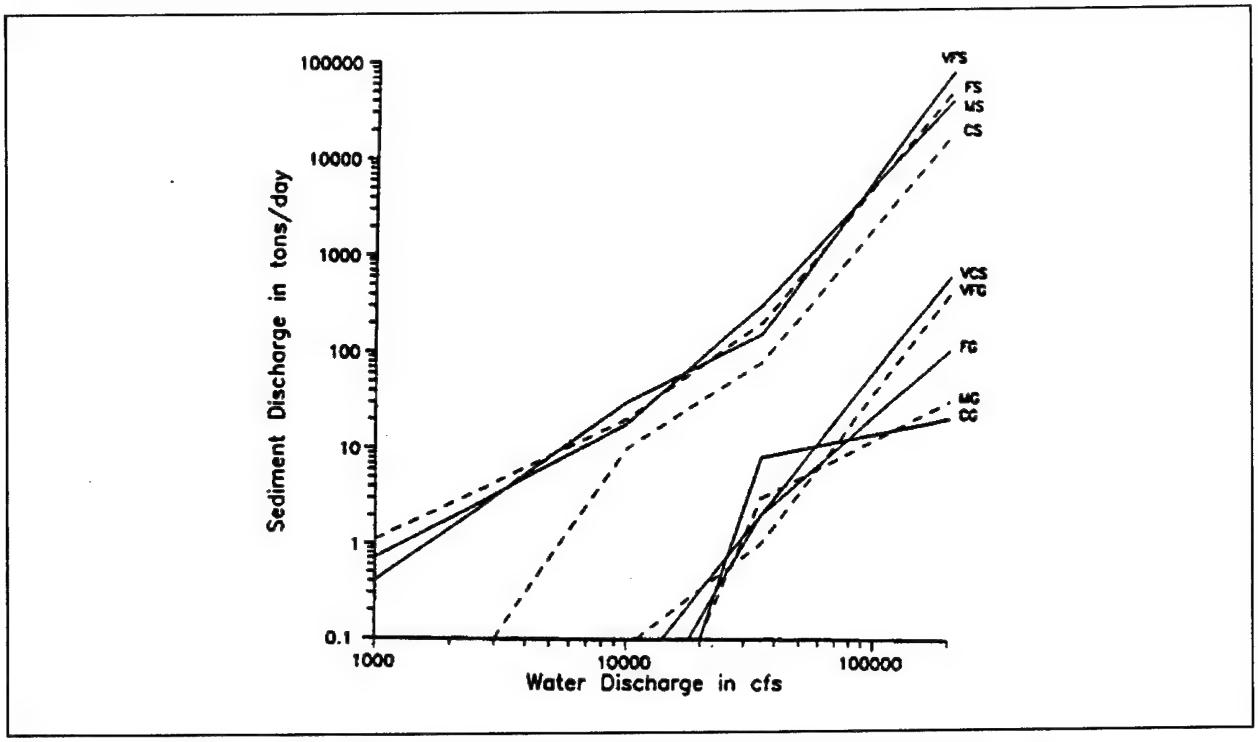

Figure 10-6. Sediment load curves

of bed-material gradation curves, the determination of the inflowing sediment discharge, and the determination of the fraction of sediment in each size class of the inflowing discharge that reflects the dominant prototype processes.

a. Roughness coefficients. The most dependable method for determining roughness coefficients for flood flows is to reconstitute measured high water profiles from historical floods. The second most dependable method is to reconstitute measured gauge records. When there are no reliable field measurements, the recourse is to use stage-discharge predictors for the movable bed portion of the cross section, as discussed in paragraph 9-11 of this manual, and calibrated photographs (Barnes 1967, Chow 1959) for the overbank and fixed bed portions. Document prototype conditions by means of photographs during the field reconnaissance.

b. Contraction and expansion losses. The information on contraction and expansion losses is more sparse than for roughness coefficients. King and Brater (1963) give values of 0.5 and 1.0 for a sudden change in area accompanied by sharp corners, and values of 0.05 and 0.10 for smooth transitions. Design values of 0.10 and 0.20 are suggested. Values often cited by the U.S. Army Corps of Engineers (USAEHEC 1990) are 0.1 and 0.3, contraction and expansion, respectively, for gradual transitions.

c. Representative data. Developing the one-dimensional representation of a three-dimensional open channel flow problem is an art. It requires one to visualize the three-dimensional flow lines in the actual problem and translate that image into a one-dimensional model. This step will often require several iterations to arrive at an acceptable model. A successful approach is to "creep" upon a solution by first running a fixed-bed model, and then adding sediment computations to simulate mobile-bed behavior.

d. Steady flow, fixed-bed tests. Start with a steady-state discharge of about bankfull. In a regime channel this is expected to be about the 2-year-flood peak discharge. Ascertain that the model is producing acceptable hydraulic results by not only reconstituting the water-surface profile but also plotting the water velocity, depth, width, and slope profiles. This test will often reveal width increases between cross sections which are greater

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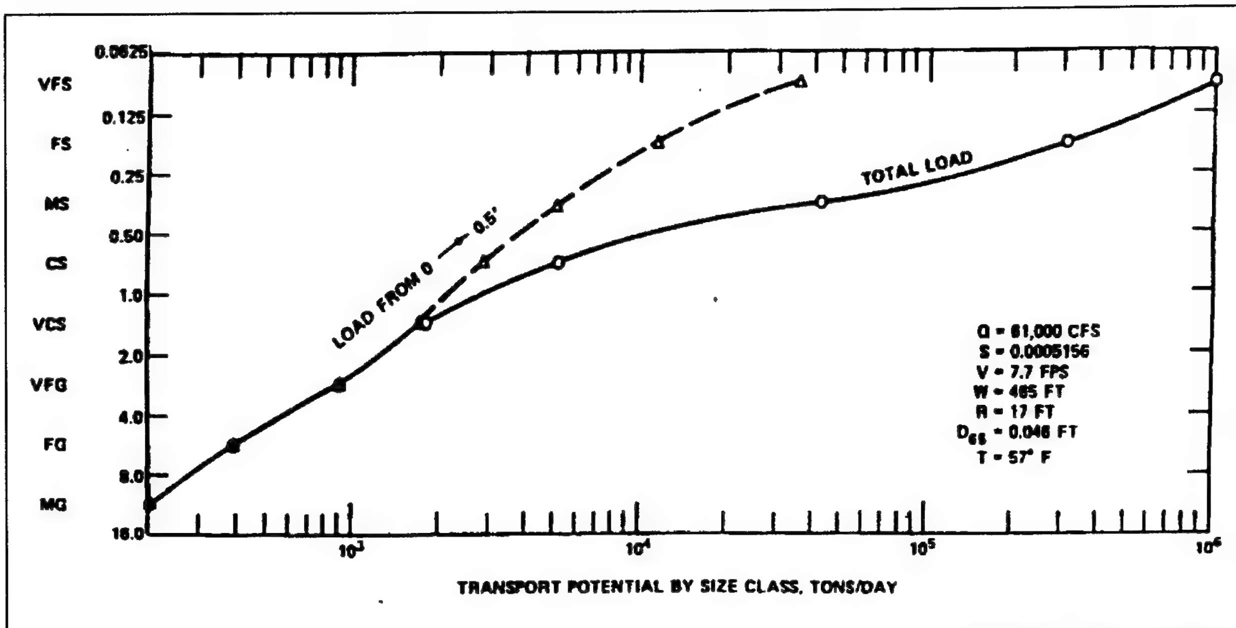

Figure 10-7. Variation of sediment transport with grain size

than the expansion rate of the fluid and, therefore, require conveyance limits. Extremely deep bend sections will occasionally indicate velocities which are not representative for sediment transport around the bend, and the recourse is to eliminate them from the model. The results from running this discharge will also give some insight as to how close the existing channel is to a "normal regime." That is, if there is overbank flow, justify that it also occurs in the prototype and is not just a "numerical problem." It is useful to repeat this steady-state, fixed-bed test for the maximum water discharge to be used in the project formulation before moving on to the movable-bed tests. The key parameters to observe are water-surface elevations, flow distribution between channel and overbanks, and velocities. However, each study is unique, and one should not regard this paragraph as a complete checklist of suggestions.

e. Steady flow, movable-bed tests. It is also useful to determine the model performance for the bankfull flow with a movable bed. Again, if the channel is near regime, this should be about a dominant discharge and result in very little aggradation or degradation. Before focusing on sediment transport, however, demonstrate that the channel roughness coefficients are appropriate for the movable boundary. Make whatever adjustments are necessary to ensure that the roughness coefficients for the streambed portion of the cross section are in reasonable agreement with that from stage-discharge predictors. Also, the sediment transport rate will usually be higher at the beginning of the simulation than it is for subsequent events because there is usually an abundance of fines in the bed samples which will be flushed out of the system as the bed layers are formed. The physical analogy is starting water to flow down a newly constructed ditch or a flume with a newly placed sand bed. It is important to balance the sizes in the inflowing bed-material load with transport potential and bed gradation. The scatter in measured data is usually sufficiently great to require smoothing, but the adopted curves should remain within that scatter.

f. Consequences of inaccurate roughness coefficients. In fixed-bed hydraulics, a range of roughness coefficients is typically chosen. The low end of that range provides velocities for riprap design and the high end provides the water-surface profiles for flood protection. In movable-bed studies such an approach is usually not satisfactory because of the feedback linkage between sediment transport and hydraulic roughness. Use of roughness coefficients which do not agree with that linkage can result in either too much degradation or too much aggradation.

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10-18. Model Circumstantiation Process

The model adjustment process is conducted to ensure that the model will reconstitute trends which have been observed in the prototype. The circumstantiation process is to change boundary conditions and rerun the model without changing its coefficients. This step establishes whether or not the coefficients which were selected in the model adjustment process will continue to describe the prototype behavior when applied to events not used in their selection. The inflowing sediment load should be changed as necessary to correspond with that during the time period selected for the circumstantiation process. This step does not ensure that the model will accurately predict prototype behavior for all boundary conditions, but it does provide additional confidence (circumstantial evidence) in model results.

10-19. Processes to Observe

a. It is important to base model performance on those processes which will be used in decision making. These usually include the water-surface profiles, flow distributions between channel and overbanks, water velocities, changes in cross-sectional area, sediment discharge passing each cross section, and accumulated sediment load, by size class, passing each cross section. A one-dimensional model may not precisely reconstitute thalweg elevations because the thalweg behavior is a three-dimensional process. Therefore, use cross-sectional end area changes and not thalweg elevation in the adjustment and circumstantiation tests. Three types of graphs should be plotted to show results. The first is "variable versus elevation." An example, the comparison of calculated stages with the observed rating curve, is shown in Figure 10-8. The second graph is "variable versus distance" for a point in time as illustrated by the water-surface and bed-surface profiles in Figure 10-9. The third is "variable versus time" at a selected cross section along the model, Figure 10-10.

b. The hydrograph used in adjustment and circumstantiation tests may extend for several years. If so, select only a few key values per year to plot. Plot the calculated water-surface elevations at all gages in the study area as well as the observed elevations that occurred at the same points in time. Evaluate model performance by computing the mean of the absolute values of error. Of course, the lower the mean value of error, the better the performance. Unfortunately, performance quality is defined by problem-specific characteristics and will probably differ from problem-to-problem. Good engineering judgment should be used to determine when the model's performance is, in fact, satisfactory or when the model requires additional adjustment.

10-20. Correcting Poor Model Performance

If the model is reproducing processes in the prototype, the key parameters should match reasonably well. These include water depths, measured velocities, measured sediment concentrations within the study reach, and bed gradations. Calculated bed gradations can be compared with sampled bed gradations by plotting the calculated active-bed gradations for computational reaches. A good way to check the reasonableness of inflowing sediment loads is to compare calculated and measured bed gradations downstream from inflow points. The following suggestions illustrate the thought process that should occur when there is an unacceptable deviation.

a. First, position the upstream boundary of the model in a reach of the river which is stable, and be sure the model exhibits that stability. That means the upstream cross section should neither erode nor deposit. Tend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse that direction for sediment problems. Do not worry about scour or deposition at the downstream end of the model until it is demonstrating proper behavior upstream from that point.

b. Second, be sure the model is numerically stable before adjusting any coefficients or processes.

c. Once the above two conditions are met, focus attention on overall model performance. Check the boundary conditions to ascertain that the particle size classes in the inflowing sediment load have been assigned "representative" concentrations. Use depth and gradation of the bed-material reservoir to determine if the model bed matches the prototype. Make plots for several different times because the gradation of the model bed will vary with the inflowing water-sediment mixture. Correct any inconsistencies in these data and try another run. If the problem persists, check the field data for possible rock outcroppings and check calculated profiles for possible errors in nearby sections.

d. If calculated transport rates are too high, check prototype data for a gravel deposit which could be forming an armor layer.

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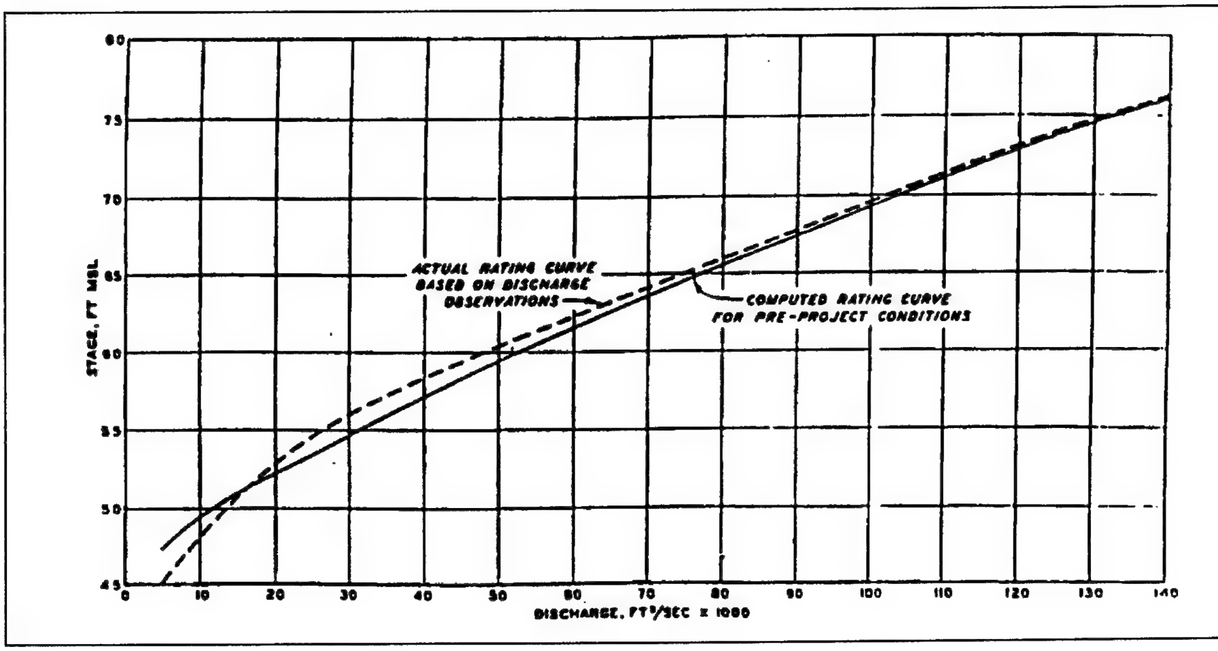

Figure 10-8. Reconstituting the stage-discharge rating curve

e. If calculated rates of deposition are too high or rates of erosion are too low, check top bank elevations and ineffective flow limits to ensure that the model is not allowing so much flow on the overbanks that the channel is becoming a sink.

f. Finally, if none of the above actions produce an acceptable performance, then change the inflowing sediment load. First use a constant ratio to translate the curve without rotation. If that is not successful, rotate the curve within the scatter of data.

10-21. Development of Base Test and Analysis of Alternatives

The most appropriate use of a movable-bed simulation is to compare an alternative plan of action with a base condition.

a. The base test. In most cases the base condition is the simulated behavior of the river under a "no action future." In a reservoir study, for example, the base test would be used to calculate the behavior of the reservoir reach of the river without the dam in place. In most cases, the base test simulation should show little or no net scour or deposition. These are the river reaches which are near equilibrium (where scour approximately equals deposition) under existing conditions.

b. Plan tests. The project alternatives can be simulated by modifying the base data set appropriately. In case of a reservoir, a dam can be simulated by inserting "operating rule data" into the base test model. For a channel improvement project, cross-sectional geometry and roughness can be changed. If a major change is required, make the evaluation in steps. Avoid changing more than one parameter at a time because that makes the results difficult to interpret. For example, it is best to analyze a channel modification project in two steps. First, change the hydraulic roughness values and simulate future flows in the existing geometry. It will be necessary to select and justify the roughness coefficients for future conditions. Justify values by consideration of proposed design shapes, depths, channel lining materials, proposed vegetation on the overbanks, probable channel debris, and calculated riprap requirements. Secondly, insert the modified cross sections and complete the analysis by simulating the alternatives to be tested. Also, select the contracting and expansion coefficients. Use model results as an aid in predicting future conditions; rely heavily on engineering judgment and look for surprises in the calculated results. These "surprises" can be used by the experienced river engineer to locate data inadequacies and to better understand the behavior of the prototype system. Any unexpected response of the model should be justified very carefully before accepting the results.

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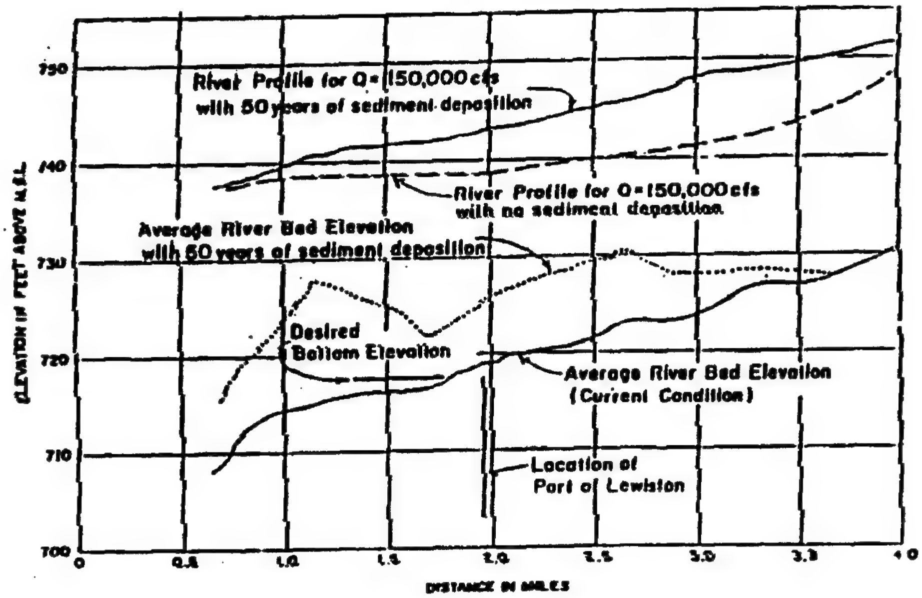

Figure 10-9. Water-surface and bed-surface profiles

c. Presentation of results. Results should be presented in terms of change from the base case rather that absolute values. This will provide an assessment of the impacts of proposed projects.

d. Sensitivity tests. It is usually desirable during the course of a study to perform a sensitivity test. Quite often certain input data (such as inflowing sediment load) are not available, or might be subject to substantial measurement error. The impact of these uncertainties on model results can be studied by modifying the suspected input data by one or two standard deviations and rerunning the simulation. If little change in the simulation results, the uncertainty in the data is of no consequence. If large changes occur, the input data need to be refined. Refinement should then proceed using good judgment and by modifying only one parameter or quantity at a time so as to be able to see the exact effect that overall changes may have. Sensitivity studies performed in this manner will provide sound insight into the prototype's behavior and will lead to the best model description of the real system.

Section V
Computer Programs

10-22. Introduction

Many computer programs are available for movable boundary simulations, and more will be created in the future. The two programs recommended for use for U.S. Army Corps of Engineers sedimentation studies are briefly discussed below. For any particular study, the need to use a different program or suite of programs may be justified. This need should be defined early in the study.

10-23. Scour and Deposition in Rivers and Reservoirs (HEC-6)

The HEC-6 code (USAEHEC 1993) is a one-dimensional movable-bed sediment model. It was formulated around Einstein's basic concepts of sediment transport; however, it is designed for the nonequilibrium case. Einstein did not address the nonequilibrium condition, but his "particle *

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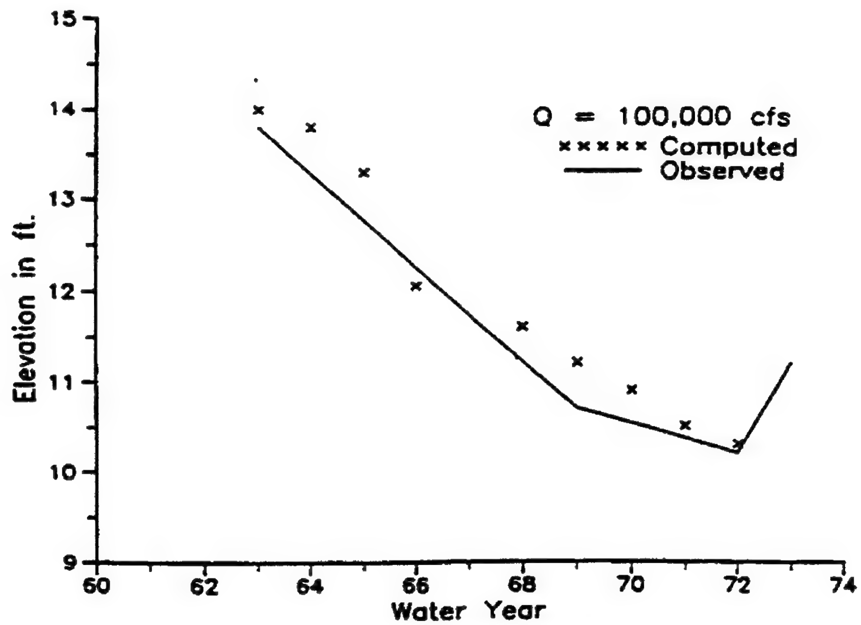

Figure 10-10. Water-surface trend plot (specific gage plot)

exchange" concept was extended by noting that when sediment is in transport there will be a continual exchange between particles in motion and particles on the bed surface. The residue may be measurable as in the case of the "bed material load," or it may be unmeasurable, as in the case of "wash load." The stability of particles on the bed surface may be related to inertia, as in the case of noncohesive particles, or that stability may be primarily electrochemical, as in the case of cohesive particles. Forces acting to entrain a particle may be primarily gravity-induced, as in the case of flow in inland rivers, or the forces may be combinations of energy sources such as gravity, tides, waves, and density currents, as in the coastal zone. Different types of sediment require different entrainment functions depending upon the propensity of the sediment to change hydrodynamic and physical properties of the flow and upon the sensitivity of the sediment type to water temperature and chemistry.

a. Equations of flow. The equations for conservation of energy and water mass are simplified by eliminating the time derivative from the motion equation which leaves the gradually varied steady flow equation. It is solved using the standard step method for water-surface profiles. The following terms are included:

$$\frac{\partial h}{\partial x} + \frac{\partial \left(\frac{\alpha V^2}{2g} \right)}{\partial x} = Se \quad \textit{(Conservation of energy)} \tag{10-4}$$

where

g = acceleration due to gravity

h = water surface elevation

Se = slope of energy line

V = average flow velocity

x = direction of flow

α = correction for horizontal distribution of flow velocity

$$Q = VA + Q_L \quad \text{(Conservation of water)} \tag{10-5}$$

*

* where

A = cross-sectional area of flow

Q_L = lateral or tributary inflow

Q = main stem water discharge downstream from tributary

V = main stem average water velocity upstream from Q_L

b. Friction and form losses. Both friction and form losses are included in the slope of the energy line; bed roughness is prescribed with Manning's n values. The model does not have a bed-form roughness predictor but n values may vary with water discharge. HEC-6 has an option which uses the Limerinos equation to calculate the channel Manning's n value.

c. Equation of sediment continuity. The Exner equation is used for conservation of sediment:

$$\frac{\partial Q_s}{\partial x} + B_s \frac{\partial Y_s}{\partial t} + q_s = 0 \quad (\textit{Conservation of sediment}) \tag{10-6}$$

where

B_s = width of bed sediment control volume

Q_s = volumetric sediment discharge rate

q_s = lateral or tributary sediment discharge rate; (-) is an inflow (+) is an outflow

t = time

y_s = bed surface elevation

d. Numerical integration scheme. The conservation of energy, conservation of water, and conservation of sediment equations are solved numerically using an explicit, finite difference computation scheme. Figure 10-11 shows a definition sketch, and the numerical forms of the equations are presented below.

$$h_2 = h_1 + \left(\frac{\alpha V^2}{2g}\right)_1 - \left(\frac{\alpha V^2}{2g}\right)_2 + H_L \tag{10-7}$$

$$Y_s(t) = Y_s(t-1) - \frac{\Delta t}{B_s}\left(\frac{(Q_{so} - Q_{si})}{(0.5 * L)} + q_s\right) \tag{10-8}$$

where

h = water surface elevation

H = energy elevation

H_L = head loss

Δt = computation time interval

L = reach length at this computation point (distance between cross-sections 1 and 3)

Q_{si} = sediment inflow to reach

Q_{so} = sediment outflow from the reach

q_s = lateral, or tributary, sediment load; outflow (+) and inflow (-)

$Y_s(t)$ = elevation of bed at time step t

$Y_s(t\text{-}1)$ = elevation of bed at time step t-1

and subscripts 1, 2, and 3 refer to cross-sections 1, 2, and 3, respectively.

e. The inflowing sediment load is prescribed as a boundary condition. The initial values of B_s and $Y_s(t\text{-}1)$ are known from cross-sections. By adapting transport functions for Q_{so}, the only unknown is $Y_s(t)$.

f. Sediment transport potential. In the HEC-6 numerical model, sediment transport formulas are restructured to adapt them for sediment movement modeling based on observations recorded by (Einstein 1950). Sediment transport potential for a size class is calculated assuming that the bed is composed entirely of that specific size class. This is based on the premise that a water discharge has the potential to move sediment whether or not sediment particles are present in the flow or on the bed. There are several sediment transport options in the HEC-6 numerical model. Given the premise that all transport capacity formulas apply to the equilibrium *

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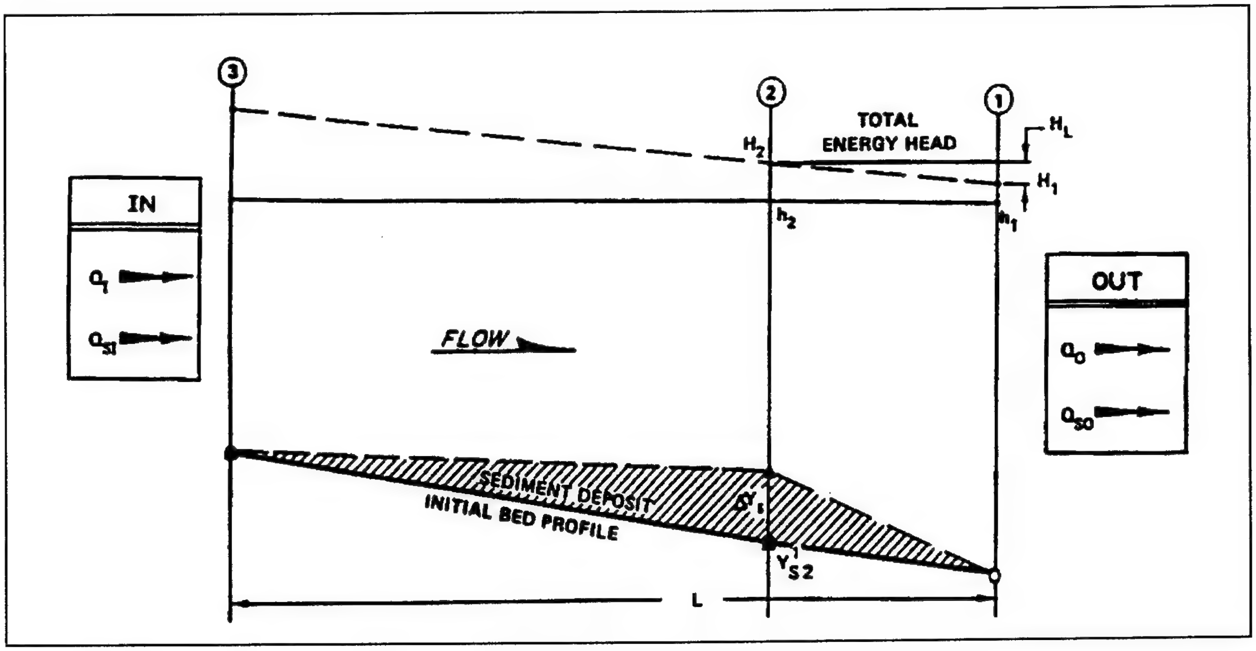

Figure 10-11. Numerical integration scheme

condition as described by Einstein, the probability that grains are present is equally significant to all even if they were not developed as stochastic formulations.

(1) Transport potential is computed for each cross-section, whether or not sediment is present on the bed surface. Subsequently, particle availability can be evaluated and expressed as a fraction of the bed surface, f_i. Availability and transport potential can then be combined during the solution of the Exner equation to give transport capacity (Q_{SO}) as follows:

$$Q_{SO} = \sum_{i=1}^{N} f_i \, Q_{Pi} \tag{10-9}$$

where

f_i = fraction of bed surface particles in size class i by weight

Q_{Pi} = sediment transport potential for size class i

n = number of size classes

(2) Transport potential can be very large for the finer particle sizes, which makes the transport capacity very sensitive to f_i. This may lead to numerical instability in the explicit solution of the sediment continuity equation which accounts for removal of specific grain sizes from the bed according to their transport capacity. The hydraulic sorting algorithm in HEC-6 breaks the computational time step into increments for solution of the sediment continuity equation, which dampens possible numerical shocks to the solution. A new value for f_i is calculated at the end of each increment. Transport capacity, then, is the accumulation of the sediment discharged during each increment over the computational time step.

(3) The concept of transport potential is what allows HEC-6 to analyze the nonequilibrium conditions such as sand moving over a gravel bed or sand and gravel moving over a hard bottom channel. The key is maintaining a control volume in the bed sediment reservoir in which the gradation of sediment is continuously updated as sediment is deposited into or scoured out of the bed. Erosion and entrainment processes seem strongly dependent on the uniformity, or lack of it, of the bed mixture. An equilibrium depth concept was established by combining flow intensity with the stability of grain sizes (USAEHEC 1993). It extends into the bed forming an active layer depth. Sediment particles are added to that layer when deposition occurs and removed from it when erosion occurs. The active layer is exchanged with the inactive layer, which lies beneath it, when the thickness becomes *

* too great. It is resupplied from the inactive layer as follows.

(4) Erosion, and removal of particles from the active layer, occurs when transport capacity exceeds the inflowing sediment concentration in a size class. The process works in increments equal to two particle diameters each. A complex sorting algorithm was developed to logically feed sediment mixtures from the inactive layer into the active layer. This process depends on availability and proceeds at a rate that recognizes the presence of a cover layer on the bed surface. The cover layer is hypothesized to develop because the transport functions move larger particles more slowly than smaller ones in the mixture and, therefore, the larger particles collect on the bed surface until an excess transport capacity removes them by erosion.

g. Time for entrainment. The time that is required for a water discharge to entrain a sufficient weight of sediment from the streambed to achieve the equilibrium condition of transport capacity is referred to as "time for entrainment." Research is needed to quantify that value. Meanwhile, some value is required, and Thomas (USAEHEC 1993) made the assumption that it could be related to flow depth. Sediment entrainment is constrained by the entrainment time in the HEC-6 numerical model.

h. Time for deposition. The characteristic time for deposition is calculated from the particle settling velocity, the flow velocity, and the water depth. In cases where the reach length is insufficient to allow for settling of a particular size through the entire water column, an adjustment is made to deposition quantities in the HEC-6 numerical model.

i. Armoring. When an armor layer develops on the bed surface, sediment particles which are smaller than the smallest size in that armor layer are no longer available from the bed source. However, f_i is a function of both the bed and the inflowing load; therefore, the inflowing load provides an exchange of particles with the bed, which creates a new f_i. That exchange between the bed and water column continues until a value for Q_{so} has been calculated for time ΔT. Gessler's (1971) work is used to determine the stability of an armor layer including particles which are larger than those transported. The equation for stability is

$$BSF = \frac{\sum_{i_{min}}^{i_{max}} P^2 f_i d_i}{\sum_{i_{min}}^{i_{max}} P f_i d_i} \quad \text{(Bed Stability Factor)} \qquad (10\text{-}10)$$

where

P = probability grains will stay

f_i = fraction of ith size class present

d_i = grain-size class interval

BSF = bed stability factor

Stability is tested at the beginning of each discharge event and if *BSF* is less than 0.65, the armor layer is destroyed. The reformation process begins immediately and is controlled by flow intensity and the inflowing sediment load.

j. The application of HEC-6. The input data file is prepared prior to accessing the program. Hydraulic computations begin at the downstream boundary and proceed cross section by cross section to the upstream boundary. Hydraulic parameters are computed and saved for sediment computations. Sediment movement computations begin at the upstream boundary and proceed section by section to the downstream boundary. At each section at the beginning of a computational time step, the volume of sediment in the bed that is available for exchange with the water column is determined. First, the stability of the armor layer stability is tested, then the equilibrium depth and active layer thickness are calculated, and an appropriate quantity of bed sediment is exchanged between the active and inactive layers. The sediment continuity equation can be solved several times during a computational time step to account for changes in the bed-material gradation of the active layer. These incremental solutions are called exchange increments and the number is specified by the user. Sediment inflow during the computational time step is equally proportioned, by size class, into each exchange increment. During each exchange increment the inflowing mass is compared with the transport capacity of each size class through the reach, and if either deposition or erosion is indicated, the outflow from the reach is adjusted by that *

* amount. The weight of the active layer is recalculated after each exchange increment calculation and the new active layer bed gradation is determined. This process is repeated for each exchange increment to numerically integrate the erosion, entrainment, transportation, and deposition during the computation time step. After the sediment movement computations are completed the resulting weight of sediment is converted to a volume, considering consolidation, and the cross section elevations are changed accordingly. The program then reads in the next hydrologic event and the process is repeated.

10-24. Open Channel Flow and Sedimentation (TABS-2)

a. Purpose. The purpose of the TABS-2 system (Thomas and McAnally 1985) is to provide a complete set of generalized computer programs for two-dimensional numerical modeling of open-channel flow, transport processes, and sedimentation. These processes are modeled to help solve hydraulic engineering and environmental problems in waterways. The system is designed to be used by engineers and scientists who need not be computer experts.

b. Description. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation problems in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure 10-12.

c. Uses. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, dispersive transport, sediment erosion, transport, and deposition, resulting bed surface elevations, and feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact of project designs on flows, sedimentation, and salinity. The calculated velocity pattern around structures and islands is especially useful.

d. Basic components of system.

(1) "Two-Dimensional Model for Open Channel Flows," RMA-2V.

(2) "Sediment Transport in Unsteady Two-Dimensional Flows, Horizontal Plane," STUDH.

(3) "Two-Dimensional Model for Water Quality," RMA-4.

e. RMAV-2V. RMA-2V is a finite element solution of the Reynolds form of the Naiver-Stokes equations for turbulent flows. Friction is calculated with Manning's equations, and eddy viscosity coefficients are used to define turbulence characteristics. A velocity form of the basic equation is used with side boundaries treated as either the slip or static. The model automatically recognizes dry elements and corrects the mesh accordingly. Boundary conditions may occur inside the mesh as well as along the edges.

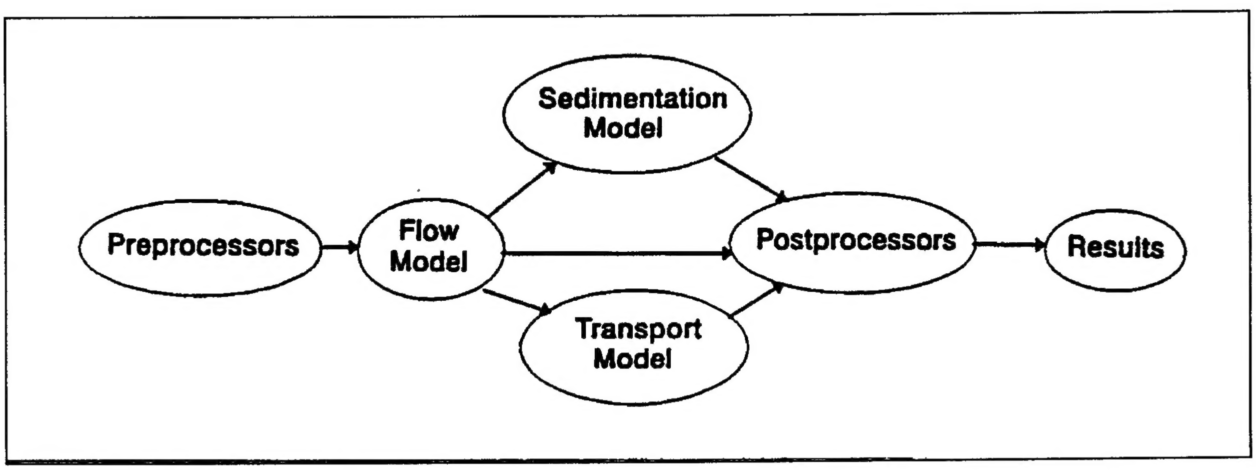

Figure 10-12. TABS-2 schematic

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* *f. STUDH.* The sedimentation model STUDH solves the convection-diffusion equation with bed source terms. These terms are structured for either sand or cohesive sediments. The Ackers-White sediment transport function is used to calculate a sediment transport potential for the sands from which the transport capacity is calculated based on availability. Clay erosion is based on work by Partheniades, and the deposition of clay utilizes Krone's equations. Deposited material forms layers, as shown in Figure 10-13, and bookkeeping within the STUDH code allows up to 10 layers at each node for maintaining separate material types, deposit thickness, and age. The code uses the same mesh as RMA-2V.

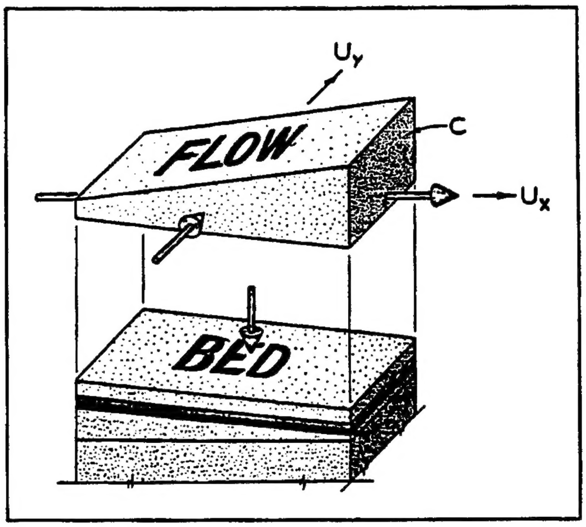

Figure 10-13. Bed layering in STUDH

g. RMA-4. Transport calculations with RMA-4 are made using a form of the convection-diffusion equation that has general source-sink terms. Up to seven conservative substances or substances requiring a decay term can be routed. The code uses the same mesh as RMA-2V.

h. System or stand-alone programs. These codes can be used as a system or each of them can be used as a stand-alone program.

i. Utility programs. A family of utility programs was developed to facilitate the preparation of input data and to aid in analyzing results.

Section VI
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